ENERGY AND COST COMPARISONS OF HPGR BASED CIRCUITS WITH THE SABC CIRCUIT INSTALLED AT THE HUCKLEBERRY MINE

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ABSTRACT

This paper summarizes a comprehensive energy and cost study comparing an existing SAG mill based circuit at Huckleberry Mine with two proposed circuits involving comminution technologies which are associated with energy efficiency: high pressure grinding rolls (HPGR) and high speed stirred mills. The specific energy requirements expressed as kWh/t for the proposed circuits were determined from pilot-scale HPGR and stirred mill testing conducted at the University of British Columbia. Samples and operating data were collected from Huckleberry's copper-molybdenum concentrator to evaluate current mill performance for comparison. To support the base case, the SABC circuit was modeled using JK SimMet® software. The main comparison focused on the complete energy requirements for each circuit, including materials handling equipment such as conveyors, screens, feeders and pumps. This paper also provides capital and operating cost estimates for each of the comminution circuits. The results showed that the HPGR - ball mill circuit achieved a 21% reduction in energy consumption over the existing SAG - ball mill circuit at the same P_{80} grind size of 160 µm. At a grind of 80% passing 75 µm, the HPGR - stirred mill circuit showed a 34% reduction in energy compared to the base case. It was concluded that the energy reduction for the new flowsheets significantly improved the economics of the Huckleberry comminution duty.

KEYWORDS

High pressure grinding rolls, Stirred mill, Semi-autogenous mill, Ball mill, Energy, Cost

INTRODUCTION

Up until now, tumbling mills such as AG/SAG mills and ball mills have had a dominant bearing on the design and economics of comminution circuits. However, it is commonly agreed that the majority of employed comminution processes are energy intensive and energy inefficient, accounting for up to 80% of overall process plant energy consumption and having an efficiency of as low as 1% (Abouzeid and Fuerstenau, 2009; Fuerstenau and Abouzeid, 2002). The U.S. department of energy reported that there is a potential to reduce energy consumption in the metals industry by up to 61% from current practice to best-estimated practical minimum energy consumption; suggestions included the implementation of best practices and the adoption of energy efficient mining and mineral processing technologies such as advanced blasting techniques, high pressure grinding rolls (HPGR) and stirred mills (U.S. DOE, 2007).

Valery and Jankovic (2002) proposed the concept of combining an HPGR and a stirred mill in a single flowsheet, which was envisioned to be an example of the future in energy conscious comminution processes. The pilot-scale HPGR and high speed stirred mill testing facility at the UBC Norman B. Keevil Institute of Mining Engineering provided a very unique opportunity to assess the HPGR and/or stirred mill circuits and understand the potential benefits. In order to examine a combined HPGR and stirred mill circuit, both machines have to be operated outside their currently accepted operating conditions. Drozdiak et al (2011) demonstrated that an HPGR - stirred mill circuit is technically feasible and showed promising benefits over the traditional stage crushers - ball mill circuit and HPGR - ball mill circuits. To determine whether the novel HPGR - stirred mill circuit arrangement could achieve energy savings in comparison to conventional SAG mill based circuits, a pilot-scale study was conducted to compare the energy requirements of the existing SABC circuit at the Huckleberry Mine to two alternative circuits: an HPGR - ball mill circuit and a novel HPGR - stirred mill circuit. The study was conducted in collaboration with the Huckleberry Mine and support from BC Hydro, Xstrata Technology and Koeppern.

TEST PROGRAM

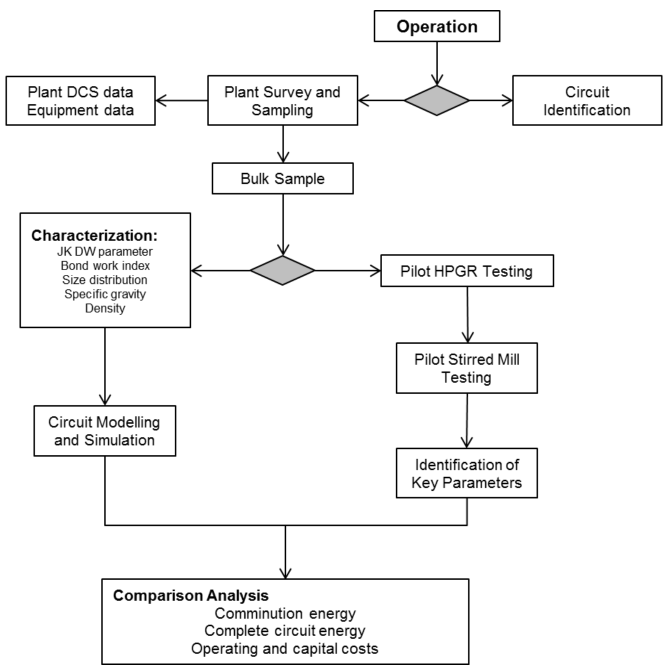

Figure 1 - Experimental program breakdown

The major components of the experimental program are shown in Figure 1. Data representative of three hours of continuous mill operation, directly preceding mill shutdown and sample collection, was analyzed to confirm process stability and subsequently to determine the actual specific energy requirement of Huckleberry process equipment. The collected sample was analyzed using established comminution laboratory testing methodologies, characterizing the properties of the ore and slurry for modelling and simulation of the circuit. The collected SAG feed sample was prepared for pilot-scale HPGR and stirred mill testing to determine the key operating parameters for flowsheet design and power-based calculations. Ultimately, the simulation and test results allowed for the direct comparison of the energy and costs of the three circuits: a conventional SABC circuit at the Huckleberry operation, an HPGR - ball mill circuit and a novel HPGR - stirred mill circuit (Figure 2, Figure 3 and Figure 4).

Circuit description

Existing SABC circuit

Figure 2 shows the current process configuration at the Huckleberry operation, which is based on a Semi-autogenous mill (SAG) operating with a pebble crusher and ball mills, commonly referred to as an SABC type comminution circuit. Modelling of the SABC circuit using JKSimMet® was carried out using known equipment parameters, operational data and the results of material analyses as inputs. The JKSimMet® model was used to confirm the validity of acquired data and to model the effects of modifying certain areas of the comminution flowsheet.

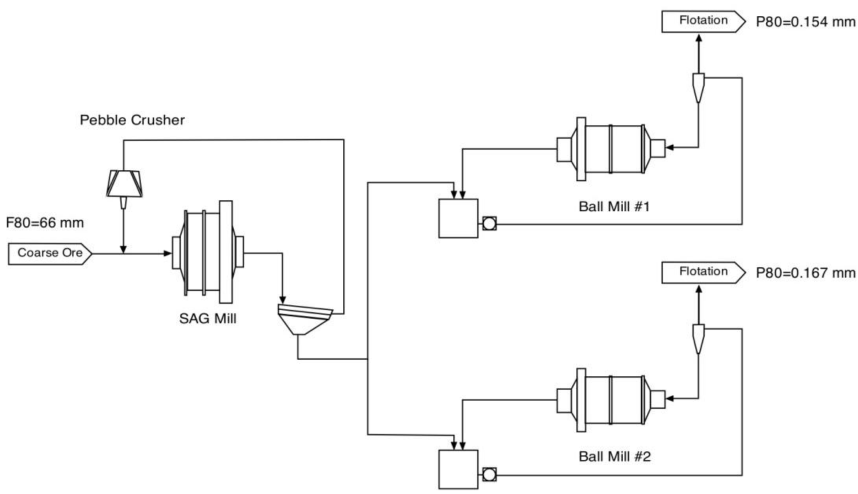

Figure 2 - Huckleberry SABC circuit - base case

HPGR - ball mill circuit

The HPGR - ball mill circuit comprises a reverse-closed secondary crushing circuit prior to a closed HPGR circuit, followed by a reversed-closed ball mill circuit with cyclones (refer to Figure 3). The vibrating screen decks were set to an aperture size of 32 and 4 mm for the secondary crushing stage and HPGR screen circuit, respectively. The energy requirements for the secondary crushing stage and the ball mill grinding stage were determined using the previously fitted JKSimMet® model of the Huckleberry mill. A number of pilot-scale HPGR tests were carried out to determine the proper operating conditions. Energy values obtained from pilot HPGR testing, laboratory testing and JKSimMet® modelling were combined to calculate the specific energy requirement for this circuit.

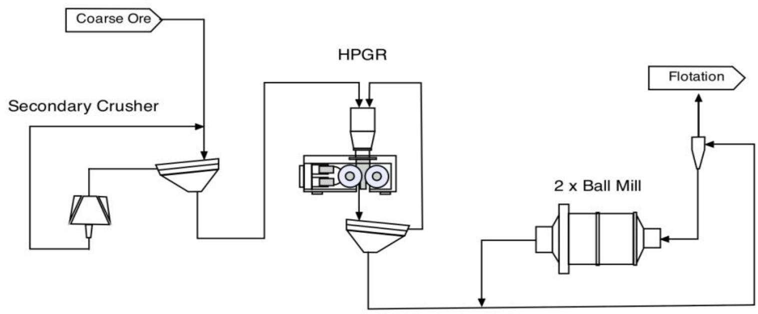

Figure 3 - HPGR ball mill circuit

HPGR - stirred mill circuit

The novel HPGR - stirred mill circuit is comprised of a reverse-closed secondary crushing circuit prior to an open HPGR circuit, and followed by a second HPGR in closed circuit to generate finer feed for high speed stirred milling (refer to Figure 4). The vibrating screen decks were set to aperture sizes of 32 and 0.71 mm for the closed secondary crushing stage and 2nd stage HPGR screening circuit, respectively. The energy requirements of the secondary crusher were determined using the JKSimMet® crusher model. A number of pilot-scale HPGR tests were carried out to determine the proper operating conditions for the first stage of HPGR crushing. Recycle tests were performed to simulate the HPGR performance in closed circuit with a screen and to determine the associated specific energy values. Energy readings obtained from pilot HPGR testing, stirred mill testing and JKSimMet® modelling were combined to calculate the total specific energy requirement for the proposed novel circuit.

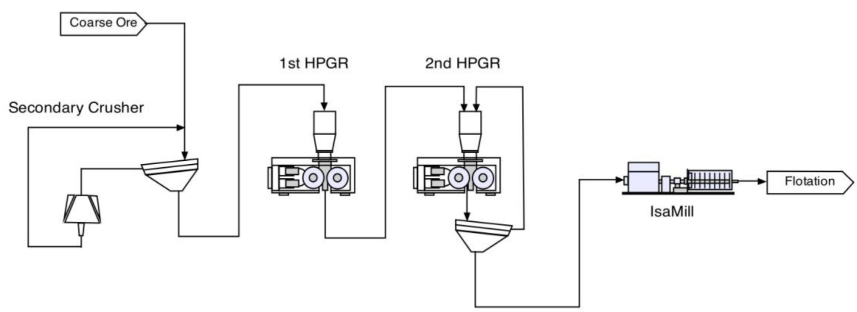

Figure 4 - HPGR - stirred mill circuit

Sample description

The sample used for this study was sourced from Huckleberry Mine, a porphyry copper-molybdenum mine located near Houston, BC Canada. A 1000 kg SAG belt-cut sample, at nominally 100% passing 100 mm, and two buckets of cyclone overflow slurry were delivered to the NBK Institute of Mining Engineering for analyses. The feed material had a moisture content of 3% with a specific gravity (SG) of 2.76. The battery limits for the energy study were established as being the feed to the SAG circuit (coarse ore stockpile) and cyclone overflow of the ball mill grinding circuit (feed to flotation circuit). The particle size distribution of the coarse ore and cyclone overflow samples are shown in Figure 5.

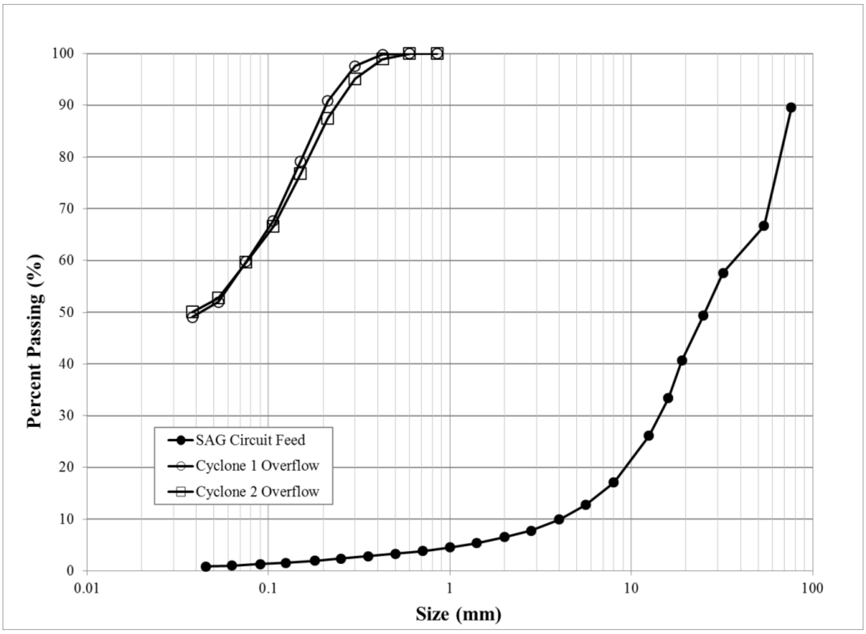

Figure 5 - Particle size distributions of plant samples

Test equipment

High pressure grinding rolls

A 750 mm diameter by 220 mm wide HPGR was manufactured by Koeppern Machinery Australia for pilot-scale testing and is located at the UBC NBK Institute of Mining Engineering. The HPGR is fitted with Koeppern's proprietary wear protection Hexadur® WTII specifically designed for comminution of high abrasive minerals. Table 1 shows the specifications of this HPGR unit. The pilot-scale unit was designed to provide test data for sizing and selection of industrial-scale HPGR units.

Table 1 - Pilot plant HPGR technical data

Parameter	Unit	Value
Roller diameter	[mm]	750
Roller width	[mm]	220
Main motor power	[kW]	200
Maximum pressing force	[kN]	1600
Maximum specific pressing force	[N/mm^2]	8.5
Maximum roll speed	[m/s]	1.57
Wear surface		Hexadur® WTII
Feed system		Gravity

The main logged instrumentation data was recorded every 200 ms and includes time, roll gap, pressing force and power consumption. The logged data in combination with machine data and sample data allowed the calculation of HPGR operational parameters such as specific pressing force, specific throughput constant (m-dot) and specific energy consumption.

Horizontal stirred mill

A Netzsch M20 horizontal stirred mill (configured with discs to IsaMill™ specifications) was used to conduct the signature plot testing for the purpose of scale-up. Signature plot tests are an industry accepted method for sizing IsaMills™ based on laboratory scale test results; a scale-up ratio of 1:1 is associated with the method (Gao et al, 1999). Table 2 summarizes the specifications of the IsaMill™ unit.

Table 2 - Horizontal stirred mill specifications

Parameter	Unit	Value
Total mill capacity	[L]	20
Effective mill volume	[L]	18.8
Main motor power	[kW]	18.6
Pump motor power	[kW]	1.5
Maximum mill flowrate	[L/min]	~ 25
Maximum shaft speed	[rpm]	~ 1200

In order to obtain a signature plot, test sample was fed through the mill a select number of times, and the power draw and product particle size after each pass were recorded. A log-log graph was then plotted using the recorded data, showing the relationship between energy input and product particle size. The specific energy requirement for an IsaMill™ in reducing particles to a desired product size could be calculated from this signature plot graph.

Other equipment

Laboratory-scale jaw, gyratory and cone crushers were used to prepare the feed sample to a top size of 32 mm for HPGR testing. A vibrating screen, Sweco® Vibro-Energy® Separator model ZS40, was used to perform all process screening work for the HPGR closed circuit tests. Particle size analyses were done on dry and wet mechanical sieve screens.

TEST RESULTS

Ore characteristic test results

The JK drop weight assessment of the SAG circuit feed sample was conducted by SGS Lakefield. The results are presented in Table 3 and compared to the JKMRC test database. The sample was characterized as being hard with respect to resistance to impact breakage (A x b) and moderately soft with respect to resistance to abrasion breakage (t_a).

Table 3 - Summary of JKTech drop weight tests

DW test parameter	Value	Relative to database rank %
A (maximum breakage)	57.90	
b (relation energy vs. impact breakage)	0.54	
A x b (overall AG/SAG hardness)	31.3	16.1
t_a (abrasion parameter)	0.59	64.2
T_{10} @ E_{cs} = 1 kWh/t	24.2	15.3

Bond ball mill grindability tests were performed on SAG circuit feed and HPGR product samples at a 150 mesh grind size (106 µm). The test results are summarized in Table 4, and indicate that the SAG circuit feed sample was characterized as hard while the HPGR product was categorized as medium hardness. The work index reduction due to potential micro fracturing was 14.4%, which is within the range reported in other studies of 5% to 15% (Amelunxen et al, 2011).

Table 4 - Summary of Bond ball mill grindability tests

Sample name	Mesh of grind	F_{80} [µm]	P_{80} [µm]	Gram per rev.	Work index [kWh/t]
SAG circuit feed	150	2,578	77	0.99	18.0
HPGR product	150	2,302	76	1.20	15.4

Simulation results

A JKSimMet® model was established and fitted for the existing SABC circuit. The main inputs were:

- Ore characteristic parameters derived from the JK drop weight test: A, b and t_a
- Bond ball mill work index
- Secondary crusher, SAG mill and ball mill machine specifications
- Secondary crusher, SAG mill and ball mill machine operating parameters
- Material properties such as % solids density by weight and particle size distribution data obtained from surveying the plant

Table 5 presents a summary of process performance, comparing plant process data with the JKSimMet® model predictions. The ball mill section for the HPGR - ball mill circuit was also simulated using this fitted model.

Table 5 - Measured and modeled process data

Description	Units	Measured	Predicted	% Deviation
Fresh feed throughput	[mtph]	766	766	0.0
SAG mill total motor power	[kW]	7435	7280	-2.1
Pebble crusher throughput	[mtph]	104	106	1.5
Pebble crusher power	[kW]	149	105.5	-29.2
Ball mill 1 motor power	[kW]	4015	4257	6.0
Ball mill 2 motor power	[kW]	4152	4115	-0.9
Cyclone 1 overflow P_{80}	[µm]	154	153	-0.5
Cyclone 2 overflow P_{80}	[µm]	167	168	0.9
Total equipment power	**[kW]**	**15,751**	**15,758**	**0.04**

HPGR pilot test results

The received SAG belt-cut sample was screened and crushed to a top size of 32 mm for HPGR testing. It was then homogenized and split into drums using a rotary splitter. A representative sample was taken for determination of the particle size distribution, Proctor density and moisture. The following HPGR feed material parameters were determined and shown in Table 6.

Table 6 - Huckleberry HPGR feed

Description	Unit	Value
Moisture	[%]	3
Specific gravity		2.76
Bulk density	[t/m^3]	1.70
Compacted density	[t/m^3]	2.10
F100	[mm]	32
F80	[mm]	23.6
F50	[mm]	14.2

A summary of the pilot-scale HPGR test results is presented in Table 7. Single-stage, two-stage and three-stage HPGR comminution was tested to provide information for the proposed process flowsheets. Pressures of 2.5, 3 and 4 N/mm^2 were chosen for the single-stage HPGR testing. Based on the results, a specific pressing force of 3 N/mm^2 was nominated as being most suitable with respect to the product size, net specific energy consumption, and specific throughput constant. For the second stage of HPGR grinding, locked-cycle testing was performed to evaluate the effect of closed circuit operation, as compared to a single pass configuration. A third stage of HPGR grinding was also assessed, however it was observed that the improvement in size reduction achieved by a third stage was too small to justify the additional energy and material handling requirements. The particle size distribution of the HPGR feed and product are shown in Figure 6. All of the HPGR product size distributions presented in this document account for the scaling of edge and centre size distributions at a ratio of 1:9.

Table 7 - Summary of HPGR test results

HPGR stage	Specific Pressing Force [N/mm^2]	M-dot [ts/hm^3]	E_{sp} net [kWh/t]	Scaled HPGR product [mm]	
				P_{80}	P_{50}
1	3	184	1.89	6.40	2.97
2*	3	217	1.45	4.05	1.85

* Results represent average response of 3 readings.

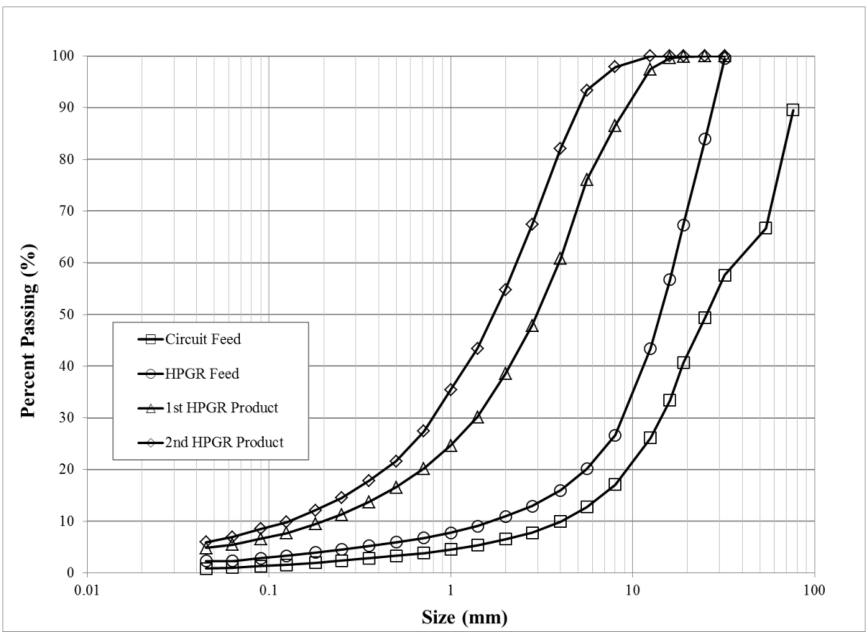

Figure 6 – HPGR feed and products particle size distribution

Stirred mill pilot test results

The HPGR product was screened at 710 μm in order to feed the IsaMill™. During screening, an observation was noted that in order to achieve a suitable degree of screening efficiency considerable effort was required to disperse the compacted HPGR product. In the laboratory this was addressed through repeated screening and manual dispersion of material on the screen bed. However, continuous industrial scale operation would necessitate specially designed material handling and classification equipment to efficiently separate the compacted material at such a fine cut-point.

With consideration of the coarseness of the feed, the experiment was performed using a graded charge of large diameter Cenotec Zirconium Silicate ceramic grinding media (50% 5.0-6.0 mm, 28.6% 4.5-5.5 mm, 14.3% 3.0-4.0 mm and 7.1% 2.0-3.0 mm). The test conditions and results are summarized in Table 8. A signature plot was obtained, which indicated that the minimum net energy required to grind the feed (F_{80} = 341 µm) to a discharge P_{80} of 75 µm was 5.1 kWh/t. This value was chosen for calculation of energy requirements for the HPGR - stirred mill circuit. The size measurements used to generate the signature plot were performed using wet mechanical screens in order to keep the size analyses consistent.

Table 8 - Summary of stirred mill test conditions and results

Description	Unit	Value
F_{80}	[µm]	341
P_{80}	[µm]	75
Feed weight	[kg]	100
Solid density	[%]	54
Flow rate	[L/min]	22
Media volume	[%]	65
Mill speed	[RPM]	1000
Specific energy	[kWh/t]	5.1

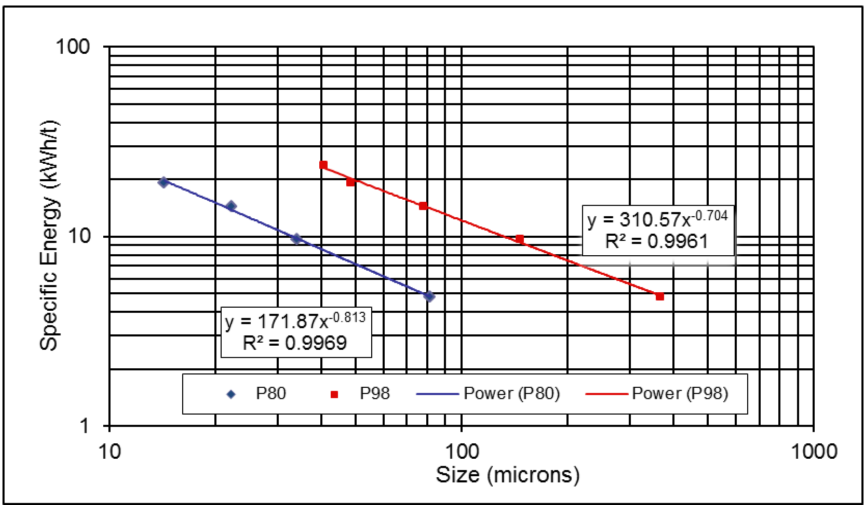

Figure 7 - Stirred mill signature plot

HPGR - ball mill circuit

Based on the pilot scale HPGR testing results, the process parameters shown in Table 9 were applied for evaluation of the HPGR - ball mill circuit. A factor of 120% of HPGR net specific energy was used to determine the total motor power draw of the HPGR for the process capacity. This value was consistent with that observed with other HPGR operations (Klymowsky et al, 2002). Modifications required for the fitted JK SimMet® model were applied for simulation of the ball mill section in the HPGR - ball mill circuit. The HPGR screen undersize was coarser than the product of the Huckleberry SABC circuit while having a lower associated Bond ball mill work index. Overall, the net effect of changing these two material attributes, size and work index, was an increase in required ball mill power for the HPGR - ball mill circuit.

Table 9 - HPGR process design parameters

Description	Unit	Value
HPGR fresh feed F_{80}	[mm]	23.0
HPGR screen aperture size	[mm x mm]	4 x 4
% passing 4 mm in HPGR product	[%]	61
Assumed HPGR screen efficiency	[%]	90
HPGR specific pressing force	[N/mm^2]	3
HPGR net specific energy	[kWh/t]	1.89
HPGR screen undersize P_{80}	[mm]	2.18

HPGR - stirred mill circuit

The process parameters shown in Table 10 were applied for evaluation of the HPGR - stirred mill circuit. Based on correspondence with Xstrata Technology, the total required IsaMill™ motor power was determined by applying a motor efficiency of 95% to the specific energy values referenced from the signature plot.

Table 10 - HPGR - stirred mill process design parameters

Description	Unit	Value
HPGR fresh feed F_{80}	[mm]	23.0
HPGR screen aperture size	[mm x mm]	0.71 x 0.71
% passing 0.71 mm in HPGR product	[%]	27.4
Assumed HPGR screen efficiency	[%]	90
1st stage HPGR specific pressing force	[N/mm^2]	3
2nd stage HPGR specific pressing force	[N/mm^2]	3
1st stage HPGR net specific energy	[kWh/t]	1.89
2nd stage HPGR net specific energy	[kWh/t]	1.45
HPGR screen undersize P_{80}	[µm]	341
Stirred mill specific energy @ target P80 = 75 µm	[kWh/t]	5.1

COMPARISON OF ALL CIRCUITS

Energy requirements

As mentioned previously, the battery limit for comparison of comminution energy using the proposed circuits was feed from the coarse ore stockpile with an F_{80} of 66 mm to two product sizes of P_{80} of 160 µm (current target grind for the Huckleberry mine) and P_{80} of 75 µm. For the target grind P_{80} of 160 µm, the existing SABC circuit was compared to an HPGR - ball mill circuit. For this product size, the IsaMill™ could not be tested because the 2nd stage HPGR product particle size (screen undersize feeding the IsaMill™) was only slightly larger than the target P_{80}, such that stirred mill grinding would be impractical. Therefore, to compare all three circuits, the target grind size was selected to be a P_{80} of 75 µm. The energy comparison, which includes energy for material handling, comminution and size classification, is summarized in Table 11 and Figure 8. The detailed simulation and calculations are not documented here.

For grinding to a P_{80} of 160 µm, the HPGR - ball mill circuit required 21% less energy than the SABC circuit. The main savings result from the lower energy required by the HPGR as compared to the SAG mill. However, an additional secondary crusher and conveyer system were required to facilitate the HPGR circuit. The HPGR also produced a coarser product than the SAG mill. Thus, the energy needed for crushing, ball milling and material handling was higher for the HPGR option than the SABC circuit. When extending the target grind size to a P_{80} of 75 µm, the energy savings of the HPGR - ball mill circuit was only 7%. The novel two-stage HPGR - stirred mill circuit demonstrated a significant reduction in energy of 34%, as compared to the SABC circuit. It must be noted that the energy for any additional equipment which would be required to disperse the HPGR product prior to screening at 0.71 mm was not accounted for. However, assuming equipment similar to that of a vertical shaft impacter (VSI) were to be used prior to screening, an overall reduction in energy in excess of 30% would still be expected. In retrospect, the study shows that the application of an HPGR - stirred mill circuit can significantly lower the energy required for mechanical size reduction.

Table 11 - Circuit energy comparison results

Description	Unit power Sim. [kW]	Quantity	Total power draw [kW]	Specific Energy [kWh/t]
766 t/h per line				
16,702 t/d @ 91% availability				
SABC base case - 160 µm				
SAG mill - 9.76 m D x 4.11 m EGL	7,435	1	7,435	9.7
Pebble crusher	149	1	149	0.2
Ball mill - 5.03 m D x 9.14 m W	4,084	2	8,167	10.7
Material handling (conveyors, screen, pumps)	736		736	1.0
			16,487	**21.5**
SABC base case - 75 µm				
SAG mill - 9.76 m D x 4.11 m EGL	7,950	1	7,950	10.4
Pebble crusher	87	1	87	0.1
Ball mill - 5.48 m D x 9.14 m W	4,540	2	9,079	11.9
Material handling (conveyors, screen, pumps)	755		755	1.0
			17,871	**23.3**
HPGR - ball mill - 160 µm				
Secondary crusher - MP 800	332	1	332	0.4
HPGR	2,778	1	2,778	3.6
Ball mill - 5.03 m D x 9.14 m W	4,420	2	8,840	11.5
Material handling (conveyors, screen, feeders, pumps)	1,162.5		1,162.5	1.5
			13,113	**17.1**
HPGR - ball mill - 75 µm				
Secondary crusher - MP 800	332	1	332	0.4
HPGR	2,778	1	2,778	3.6
Ball mill - 5.03 m D x 9.14 m W	6,067	2	12,134	15.8
Material handling (conveyors, screen, feeders, pumps)	1,385		1,385	1.8
			16,629	**21.7**
HPGR - stirred mill - 75 µm				
Secondary crusher - MP 800	332	1	332	0.4
1st HPGR	1,520	1	1,520	2.0
2nd HPGR	2,365	2	4,730	6.2
IsaMill	1,381	3	4,143	5.4
Material handling (conveyors, screen, feeders, pumps)	1,056		1,056	1.4
			11781	**15.4**

Note that, there was a discrepancy in the additional power required to reduce the final product size from 160 to 75 µm for SABC circuit and HPGR - ball mill circuit. The HPGR - ball mill circuit when grinding to 75 um compared to 160 um used an extra 4.6 kWh/t, but for the SABC circuit it only used an extra 1.8 kWh/t. It is because that the reported SABC circuit power for the 160 µm grind size was based on actual site data. JKSimMet® was used to fit a model to site DCS data. Thus, there was considerable scope to reduce the ball mill power consumption by using smaller ball mill grinding media. However, for a final grind of 75 µm, the reported power values for both HPGR - ball mill and SABC circuits were based on JKSimMet® modelling alone. In these cases, the previously fitted model was optimized through process design changes (media size, transfer size, cyclone parameters etc.) to achieve the 75 µm product size while minimizing energy consumption. So the difference in ball mill power to reduce the final grind size from 160 to 75 µm should have been much greater in the case of the SABC circuit than actually reported.

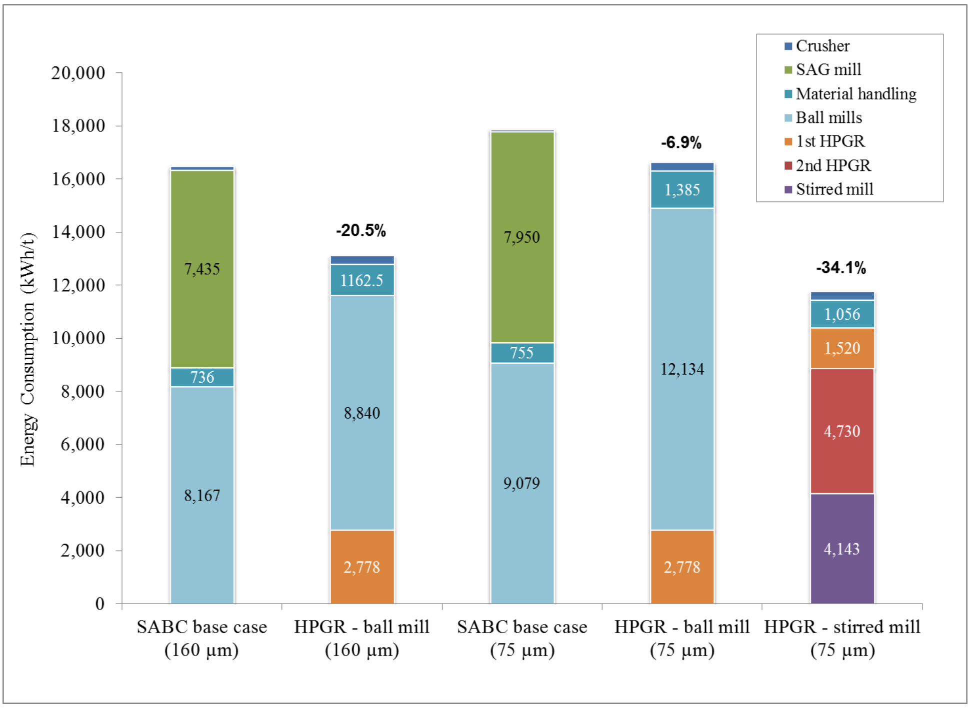

Figure 8 - Comparison of total circuit energy requirement

Capital and operating costs

To complete the comparison of the process options, capital and operating costs were determined from vendor quotes and installation costs. The costs are deemed to have an accuracy of ±50% to a preliminary level of assessment. For comparison, the costs for SABC circuits grinding to 160 µm and 75 µm were determined to allow for direct comparison to HPGR - ball mill and HPGR - stirred mill circuits, respectively. The capital and operating cost estimates are shown in Table 12 and Table 13, respectively. The indirect cost was estimated at 45% of direct capital costs and was considered to be within industry standards for the options contained in this paper. A similar approach was applied to estimate the total direct costs. It was found that both HPGR - ball mill and HPGR - stirred mill circuits have higher associated capital costs than the SABC option. Conversely, operating costs for the two proposed circuits are substantially lower, which relates directly to lower energy consumption levels.

Table 12 - Summary of capital cost estimate

Description	Unit	SABC 160 µm	SABC 75 µm	HPGR - ball mill	HPGRs - stirred mill
Equipment cost	[M$]	36	38	39	47
Total direct costs	[M$]	109	115	125	149
Total indirect costs	[M$]	49	52	56	67
Total capital cost estimate	[M$]	158	167	181	216

Table 13 - Summary of operating cost estimate

Description	Unit	SABC 160 µm	HPGR - ball mill 160 µm	SABC 75 µm	HPGR - ball mill 75 µm	HPGRs - stirred mill 75 µm
Energy	[M$/yr]	6.6	5.2	7.1	6.6	4.7
Maintenance	[M$/yr]	3.3	3.8	3.5	3.8	4.5
Consumables	[M$/yr]	12.0	7.4	12.9	9.5	8.9
Labor	[M$/yr]	0.4	0.5	0.4	0.5	0.5
Total	[M$/yr]	22	17	24	20	19
Total	[$/t]	3.7	2.8	3.9	3.3	3.0

Trade-off economics

The trade-off economics were calculated on the basis of net present value (NPV). A discount rate of 5% and a 15-year mine life were assumed. At a grind of 80% passing 160 µm, the HPGR - ball mill circuit shows significant cost advantage over the SABC circuit with a NPV of $33 million and an IRR of 22% (Table 14). At a product size of 80% passing 75 µm, both options have costs advantages over the SABC option, although the HPGR - ball mill circuit had lower overall costs than the two-stage HPGR - stirred mill circuit. In general, a finer grind size would not be selected unless it resulted in significant recovery improvements. Since the copper-molybdenum recovery versus grind size information was not available, such a comparison was not possible for the present study. However, in cases where a finer primary grind is needed to achieve high metal recoveries, the two-stage HPGR - stirred mill process demonstrates significant energy savings that would be reflected in the NPV.

Table 14 - Net present value and internal rate of return

Description	Unit	HPGR - ball mill v.s. SABC @ 160 µm	HPGR - ball mill v.s. SABC @ 75 µm	HPGR - stirred mill v.s. SABC @ 75 µm
CAPEX difference	[M$]	-23	-14	-50
OPEX difference	[M$]	5	4	5
NPV @ 5%, 15 years	[M$]	33	22	5
IRR	[%]	22	23	7

DISCUSSION

Evaluation of the proposed circuits showed that combining the two comminution technologies, HPGR and stirred mill, had considerable potential as an energy efficient and economic approach to grinding metallic ores. Overall, the proposed HPGR based circuits were found to be more energy efficient than the current Huckleberry SABC circuit. Both the higher energy efficiency and elimination of steel grinding media associated with the HPGR based circuit significantly reduced the determined operating costs. The effect of ore variability was not evaluated in this study; however, HPGRs are certainly less sensitive to variation in ore hardness when compared to SAG mills. There is also a question of the differences in liberation characteristics from a SAG mill - ball mill operating in closed circuit with a classifying cyclone and the HPGR - stirred mill operating in open circuit. With differences in particle breakage mechanisms as well as mineral particle size distributions (since no cyclone classification is used in stirred mill operation), it would not be surprising to find differences in degree of liberation. During pilot simulation of the HPGR - stirred mill circuit, both machines were operating outside their respective industry standard conditions. Challenges were primarily associated with the nominated transfer size between the HPGR and stirred mill. For example, nomination of a coarser transfer size necessitated the use of larger stirred mill grinding media and resulted in a reduction in stirred mill energy efficiency. Conversely, nomination of a finer cut-point was detrimental to the screening efficiency of HPGR product. Successful development of the HPGR - stirred mill circuit relies on further addressing the efficient separation of HPGR product at a suitable feed size for stirred mill operation. This will likely involve the introduction of an additional piece of material dispersing equipment which would be located prior to the HPGR screens.

CONCLUSIONS & RECOMMENDATIONS

The presented study built on previous related work at the UBC NBK Institute of Mining and showed that an HPGR - stirred mill grinding circuit, as an alternative to commonly implemented SABC comminution circuits, has significant potential as an energy efficient alternative. A reduction in energy consumption of 34% was determined to be attainable through implementation of the HPGR - stirred mill circuit when targeting a final P_{80} grind size of 75 micron. Project economics were also in favour of the proposed circuit and would further improve in regions where energy supply is more expensive than the relatively low energy unit costs used as a basis for this evaluation.

Other advantages identified with the proposed circuit include the resilience of HPGRs and stirred mills to changes in ore hardness. Carrying out further pilot tests using samples taken from different areas of the Huckleberry deposit would allow for this attribute to be quantified in terms of its influence on energy requirements and overall project economics.

Further work is required to improve the classification of HPGR product and to optimize stirred mill parameters for treating coarser feed sizes. The former is particularly challenging when taking into account the detrimental effect of moisture on HPGR performance, thereby necessitating a dry classification process to limit the amount of moisture returned to the HPGR grinding section with oversize particles.

The results of this study clearly show that there is considerable scope for improving the energy efficiency of industry standard comminution grinding circuits. The proposed HPGR - stirred milling has demonstrated significant potential as a mean to grinding more efficiently, this attribute being increasingly important as the mining industry is faced with extracting metals from harder and more complex deposits.

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