

How energy efficient is HPGR?

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The world is rapidly becoming more 'green' i.e. energy conscious. Since mining and mineral processing are massive energy users, the mining industry is seeking ways to reduce its energy footprint. In mining and mineral processing operations, energy is often the most expensive cost item. Comminution, i.e. grinding, is frequently the most energy-intensive step between mine and metal.

High pressure grinding rolls (HPGR) are being installed in a rapidly growing number of 'hard rock' mineral processing operations. In the energy conscious cement industry, HPGR grinding has been standard practice for decades. HPGR is known to be energy-efficient; the question is how energy efficient? How can the energy efficiency of HPGR be enhanced?

This paper reviews recent HPGR applications for the processing particularly of copper, gold, platinum, PGM-Ni-Cu and iron ores. HPGR technology is discussed with respect to energy efficiency. The harder the ore the greater the energy savings are likely to be.

Typical energy savings of 10–20% can be expected when installing HPGR vs. a SAG mill. Wipf (2005) showed why conventional Bond Work index tests on HPGR product is likely to underestimate the energy savings that can be achieved by installing HPGR.

Energy efficiency of HPGR is, however, ore-specific. The biggest energy savings of HPGR tested thus far is 9.5 kWh/tonne claimed for Vista Gold's Mt. Todd gold ore from Western Australia, a savings of over one-third of conventional SABC comminution energy.

Several commercial scale iron-ore pellet feed plants install HPGR for fine-grinding of concentrate to increase the surface area of pellet feed in a manner that reduces overall energy consumption.

Energy-consumption in comminution is, however, only part of the energy savings benefit story. HPGR typically also reduces the amount of steel lost through wear of mill liners and media. Marsden (2008) showed that when the energy that would have been consumed to produce the steel that is saved by applying HPGR is factored in, then the overall energy savings of HPGR is considerably greater.

Johnson *et al.* (1988, 2005) tested HPGR in a flowsheet in which energy savings of around 50% can be expected if HPGR product screen oversize is recirculated to the HPGR.

Innovative flowsheets have been proposed by Rule *et al.* (2008) and by Morley (2008) which are expected to result in significantly increased energy savings.

HPGR applied in flowsheets in conjunction with coarse ore separation devices, e.g. ore sorting or DMS to remove barren waste from HPGR feed promises significantly greater energy efficiencies.

Fine-grinding and ultra-fine grinding of ore or concentrates in conventional ball mills results in energy consumptions that increase exponentially with product fineness. Wipf (2009) presented a flowsheet in which he proposed the installation of HPGR ahead of the Aerosion 'Disintegrator' for ultra-fine grinding of ores and/or concentrates. This dry grinding arrangement is expected to achieve a p80 = 7 μm using up to 100 kWh/t less energy than could be achieved by wet ball milling.

Using conventional comminution, an ore might require grinding to p80 = 45 μm (- 325 mesh), for example, to liberate the valuable components, e.g. magnetite, from gangue, e.g. silica. Inter-particle comminution in HPGR may break some ores along grain boundaries thereby liberating valuable minerals from gangue at a much coarser particle sizes. Early magnetic separation rejection of silica gangue liberated from magnetite by HPGR at coarser grain sizes could further reduce downstream comminution energy consumption.

Introduction

Daniel (2008) summed up the situation succinctly: 'Although it is recognized that the energy efficiency of most comminution devices, especially ball mills, is generally very poor, how efficiently energy resources are used in the future will become more important. Sustainability drivers such as energy efficiency are soon to play a very important role in a mine's triple bottom line, and as such innovative ways of improving overall energy

efficiency such as the application of High Pressure Grinding Rolls (HPGR) is now being pursued.'

The world is rapidly becoming more 'green' i.e. energy conscious. Since mining and mineral processing are massive energy users, the mining industry is seeking ways to reduce its energy footprint. In mining and mineral processing operations, energy is often the most expensive cost item and comminution, i.e. grinding is frequently the most energy-intensive step between mine and metal.

This paper reviews what others have observed and published about HPGR applications particularly with respect to energy efficiency of HPGR technology. Quoting Mike Daniel (2008) again: ‘The energy efficiency of most comminution devices, in particular that of ball mills, is generally very poor...’

‘Innovative research in High Pressure Grinding Rolls (HPGR) technology is being pursued nowadays as a means of improving overall comminution energy efficiency.’

There are three aspects to this review of energy efficiency in mineral processing. First is the quest to find less energy-intensive comminution technologies. Second is to find ore processing flowsheets that consume less energy overall; and third is to take into account indirect big picture considerations such as energy-saving equivalents embodied in the consumption of less grinding media and mill liners that require energy to produce.

Marsden (2009) showed that HPGR, in one case with which he is intimately familiar, offered the following advantages over SAG mills:

- 2.4 kWh/t vs 12.0 kWh/t
- Greater flexibility
- Lower unit cost.

Of course, the installed power for HPGR/Ball mill circuits vs SAG/Ball Mill circuits are generally beneficial but nothing like as advantageous as this, however the above number offers a big incentive to plant designers. Disadvantages to be weighed include greater capital cost for the entire plant including crushers, screens, conveyors, dust control, etc.

Schoenert K. (1979) reviewed energy aspects of comminution. At that time there were no HPGR installations in hard-rock ore applications.

Parks (2000) wrote: ‘Although HPGR does save power and reduce wear in downstream mills, the most interesting concept is the metallurgical benefits.’ Since then, of course, power and steel costs have escalated and reducing energy and wear part consumption have become important driving forces.

Maxton *et al.* (2002) reiterated Fuerstenau *et al.* (1991) in stating, ‘Commonly, the primary motivation for the use of HPGR as a comminution alternative is its energy efficiency when compared to conventional crushers and mills. This improved efficiency is due to the determinate and relatively uniform loading of the material in the HPGR compression zone, whereas the loading in crushers and (particularly) mills is random and highly variable, and therefore inefficient.’

Fourteen years before, von Michaelis (1988) wrote: ‘HPGR technology from Germany has demonstrated several advantages including reduction in comminution power consumption. Better grain boundary breakage is claimed to reduce over-grinding which is important ahead of flotation...’

O’Bryan and Wipf (1995) (who at that time were employed by a SAG mill supply company) pointed out that although SAG milling was well entrenched after four decades since first gaining acceptance, however, ‘compression comminution is the most energy efficient form of comminution. The high pressure roll crusher with compression as the dominant comminution mechanism was recognized as an up-and-coming contender of interest to industry particularly for the energy savings that it offered.’

An industry observer made the comment that anyone who regularly attends the SAG conferences cannot help concluding that hundreds of presenters describing their

attempts to control SAG mills and to improve their efficiency must be an invitation to find a more efficient comminution system. Another industry leader went so far as to comment that the name ‘SAG Conference’ needs to be changed to ‘Comminution Conference’ to reflect the growing role of HPGR in a world where SAG and SABC were more or less standard.

Numerous HPGR machines have subsequently been installed in commercial scale ‘hard rock’ comminution applications and many additional ores have tested favourably for HPGR amenability.

This paper reviews the empirical observations and conclusions with respect to energy efficiency of HPGR of researchers and application engineers involved in the operation of HPGR. Numerous additional examples of HPGR power savings relative to SAG-ball mill circuits and crusher-ball mill circuits exist but cannot be reported due to client confidentiality limitations. This compilation of examples from the literature is therefore far from complete, but is encouraging nonetheless.

HPGR machines have been installed for the treatment of limestone, cement and kimberlite ores for several decades. Application of HPGR in ‘hard rock’ comminution circuits is relatively new although several kimberlites (up to 15 kWh/t) and lamproites (up to 18 kWh/t) are every bit as hard as the typical copper ore (15–16 kWh/t). Patzelt *et al.* (2001) showed that ‘HPGRs have proven themselves in AG and SAG mill circuits in the iron ore industry. Considerable interest in their application to harder copper and gold ores has been aroused. The main attraction of these units is that they can treat high capacities, and generate a product that reduces energy consumption and increases grinding capacity in downstream ball mills. With the introduction of larger cone crushers to match the capacities of the large HPGRs, new circuit concepts are being developed which challenge SAG mills themselves. Today, large hard rock projects are considering using two of the largest cone crushers and HPGRs for the production of 3 000 tph of minus 10 mm ball mill feed. The product obtained from HPGRs has a much higher fines content than that which could be obtained from conventional crushers, even at fine settings, and thus has the potential for significantly increasing grinding capacity in ball mills. Furthermore the higher fines content and reduction in work index due to the formation of micro-cracks from the application of high compressive forces results in lower circulating loads in ball mill circuits. This alleviates problems of handling high throughputs in respect to selection of pumps and cyclones. The advantage of employing a single HPGR unit was first seen in a Chilean iron ore mine. There, one HPGR is operated in closed circuit to produce more than 1 000 tph of –6 mm product from a 65 mm feed material. The lifetime of the wear protection was more than 8 000 hours. Power consumption was about 1.3 kWh/t. It was the substitution of multiple third and fourth stage crushing units with a single HPGR that made this project feasible at all.

Hard rock HPGR applications up to 2009

‘Hard rock’ operations that use HPGR as an alternative or supplement to conventional comminution equipment include:

- Argyle, Ekati and Voorspoed (lamproite and hard kimberlite diamond ores)
- CMH Los Colorados and Empire (iron ore)

- GoldCorp Penasquito, Bendigo, Suchoj Log, Tarkwa, and Boddington (gold ores)
- Northam Platinum (UG2) and Anglo Platinum (Platreef)
- Freeport McMoRan Grasberg and Cerro Verde (copper).

In addition pilot and commercial-scale HPGR tests have been conducted at:

- Boddington, W.A. (gold-copper)
- Cyprus Sierrita, AZ (copper, 1994–1995)
- Mt. Todd, NT (gold)
- Lone Tree, NV (gold)
- Pilot plant tests at several mining company laboratories
- Hundreds of ore tests at Public mineral processing labs such as SGS Orestest; SGS Lakefield, Mintek, AMMTEC, AMDEL, JKMRC, etc.
- Hundreds of tests at HPGR supplier laboratories.

Energy-efficient process selection

Pokrajcic *et al.* (2009) showed that a 4 million tpa copper/gold concentrator in NSW, Australia could reduce the installed energy requirement from 16.8 MW for a plant with SAG/Ball mill circuit (80% direct, 20% indirect energy) to 10.5 MW (92% direct, 8% indirect) by selecting a circuit comprising HPGR/AG mill and pebble mill.

Johnson *et al.* (1995, 2005) found that by closing the circuit around a high pressure grinding roll machine, and by closing the circuit at a fine screen size, it is possible to dramatically reduce comminution energy consumptions compared to conventional comminution circuits. For the ore tested in that programme a reduction of over 50% in the comminution energy was observed. Others have installed two HPGRs in series in pilot plants but their results have not yet been published and a commercial plant with this configuration is still awaited.

Marsden (2008) found that hydrometallurgical processing of copper concentrates consume substantially less energy than pyrometallurgical processing of copper concentrates. He investigated the total energy consumption per pound of copper produced comparing different comminution flowsheets and found that those in which HPGR is used following crushing were significantly more energy efficient than those employing SAG-ball mill circuits. Heap and dump leaching technology, on the other hand, produces the most energy-efficient copper although metal recovery is generally not as efficient.

Crushing—HPGR – Ball Milling – Flotation – Smelting was found to be significantly more energy-efficient than the same flowsheet with SAG milling instead of crushing-HPGR. If the energy equivalence of SAG mill media and liner wear were to be taken into account, then the relative energy efficiency of HPGR would be even greater.

Crushing—HPGR—ball milling – flotation – concentrate Leaching – Direct EW was found to be the most energy efficient overall flowsheet, other than heap and dump leaching. The latter are less efficient because metal recoveries are lower than circuits employing grinding.

Marsden (2008) found that HPGR, while not involved directly in the hydrometallurgical step, was estimated to provide an energy savings of 3 742 kJ/lb Cu compared with SAG milling (SABC configuration) representing a 13% overall energy reduction. 54% of the energy reduction (2 038 kJ/lb Cu) is related to wear steel energy equivalent (SAG mill liners and ball consumption) and the remaining 1 705 kJ/lb Cu is lower electric power consumption (lower efficiency of size reduction in the SAG mill versus HPGR).

Marsden (2008) also pointed out that the use of HPGR as a secondary, tertiary or quaternary crushing step (or for combinations of these steps) is expected to provide significant benefits to copper efficiency via subsequent heap leaching due to micro-fracturing within host rock particles and improved product size distribution (less super-fine sliming, better size distribution, for improved mineral liberation and/or better exposure to lixiviant solution). Klingmann (2005) reported similar benefits resulting from the application of HPGR for heap leaching of gold.

Why use HPGR?

Morley (2005, 2003) states: ‘Commonly the primary motivation for the use of HPGR as a comminution alternative is its energy efficiency when compared to conventional crushers and mills. This improved efficiency is due to the determinate and relatively uniform loading of the material in the HPGR compression zone, whereas the loading in conventional crushers and (particularly) tumbling mills is random and highly variable, and therefore inefficient...

‘These effects can be attributed to the phenomenon of micro-cracking of individual progeny particles due to the very high stresses present in the HPGR compression zone ...’

‘In addition to being ore-dependent, the extent of micro-cracking is a direct function of the operating pressure— and therefore energy input of the HPGR, and in any given operation, the benefits of micro-cracking must be weighed against the incremental power required to achieve those benefits.

Anguelov *et al.* (2008) presented the results of HPGR trade-off studies carried out for six different hard rock ore processing projects including two 30 000 tpd copper concentrators one for Pacific Booker Minerals and one for Imperial Metals. In both cases the HPGR option indicated a gross power consumption reduction over a similar conventional SAG mill grinding circuit. Overall operating cost savings were of the order of 15%. Capital costs for the HPGR option was slightly higher than the SAG mill option, but was considered to be the same within the accuracy level of their study.

Von Michaelis (2005) concluded that ‘Higher energy and steel prices provide a significant incentive for industry to consider technologies such as HPGR that reduce energy and steel consumption.’ ... ‘Conventional mills are by their very nature notoriously energy-inefficient. For many mines, energy is the single biggest cost item. HPGR offers a way to save significant amounts of energy.’

HPGR has been selected for several mines. The following summarizes some of them:

Adanac Molybdenum Corporation – Ruby Creek project, Atlin, B.C.

Anguelov *et al.* (2008) described a trade-off study of HPGR vs. SAG milling for this 20 000 tpd open pit mine and concentrator to produce a high-grade molybdenite concentrate from a low-grade resource. Site power was to be supplied by diesel power for the first 5 years of operation at a time when diesel fuel prices were at an all-time high. Results of the trade-off study indicated that HPGR at Ruby Creek would achieve process operating cost savings in excess of 25%. In addition, the introduction of a second HPGR would increase the availability of HPGR to 96 compared with SAG mill process availability of 91%. Power requirements of the grinding circuit with HPGR

would be reduced by more than 4 kWh/tonne compared with the SAG-ball mill option. According to Anguelov *et al.* (2008) the HPGR product size would be 3.8 mm and the ball mill grind would be -220 μm . Power cost was projected to be reduced by replacing SAG with HPGR from US\$4.53/t for SAG-ball mill to US\$3.83/t for HPGR-ball mill, and comminution wear part costs were projected to be decreased from US\$0.77/t for SAG-Ball Milling to US\$0.73/t for HPGR-ball milling. Regretably, the Ruby Creek molybdenum project was by the economic downturn and the project has not yet been constructed, i.e. a milling + wearpart energy equivalent reduction from \$5.30/t to \$4.56/t.

Anglo American Los Bronces Copper concentrator, Chile – HPGR test programme

Oestreicher and Spollen (2006) describe in detail the evaluation of HPGR for tertiary crushing ahead of ball milling compared with an SABC circuit for an 80,000 tpd expansion at Los Bronces. Initial laboratory test work undertaken at Anglo Research and reported by Smit (2005) indicated significant potential improvements in copper recovery to a rougher concentrate through the application of HPGR for Los Bronces ores, employing an innovative flow sheet. HPGR test work at Anglo American Research in Johannesburg and at Polysius' laboratories in Beckum, Germany showed a general and consistent reduction in ball mill work indices with increasing HPGR roll pressures in the open circuit samples.

According to Oestreicher and Spollen (2006) 'In the closed circuit—locked cycle test the level of reduction in Bond ball mill work index is 17% for sample A and 12% for samples B and C. It is assumed that this reduction is a result of micro-cracking or other compressive force effects on the samples produced by the action of the HPGR.'

Oestreicher & Spollen described an HPGR-Ball mill circuit in which two 2.4 m diameter x 1.75 m HPGRs each fitted with 5 600 kW would treat feed of 98% -50 mm in closed circuit with an 8 mm-aperture screen the undersize of which feeds two 7.53 m diameter x 11.25 m 13 800 kW ball mills.

Oestreicher and Spollen (2006) reported that the operating cost of the HPGR-ball mill circuit would be US\$1.48/tonne compared with US\$1.85/tonne for the SABC circuit.

Specific energy consumption for the HPGR-ball mill circuit including all ancillary equipment was estimated to be 13.02 kWh/t compared with a calculated value of 16.21 kWh/t for the SABC circuit.

Oestericher and Spollen (2006) concluded that the HPGR-ball mill circuit offered an estimated operating cost advantage of US\$0.37/t over the SABC circuit. This operating cost advantage of the HPGR-ball mill circuit was made up from the following:

- *Energy savings*—estimated to be lower by US\$ 0.22/t reflecting the lower energy consumption per tonne of the HPGR—ball mill circuit at 13.02 kWh/t compared with a calculated value of 16.21 kWh/t for the SABC circuit
- *Material cost savings*—estimated to be US\$0.15/t reflecting a 5 000 hour average life for roll tyres and savings in grinding media and liners.

Oestreicher and Spollen (2006) reported a capital cost for the HPGR-ball mill circuit at US\$266.7 million, which was US\$38.5 million higher than for SABC, the difference being mainly for the additional 30 000 tonne intermediate storage stockpile and the associated conveyors between the HPGR and ball mill circuits.

Specific energy consumption in the HPGR closed circuit locked cycle test was 2.53 to 2.73 kWh/t of fresh feed.

Circulating load obtained from the oversize to undersize ratio after 3 cycles was steady at 70–80% for all Los Bronces ore types tested.

There appeared to be a general and consistent reduction in ball mill work indices with increasing HPGR roll pressure.

Simulations indicated that two HPGRs and two ball mills would be capable of grinding 80 000 tpd ore under the design conditions with a preferred screening size between the HPGR and ball mill circuits of 8 mm. Total circuit energy 25% was achieved relative to conventional SABC.

The HPGR-ball mill circuit operating cost of US\$1.48/t versus SABC circuit cost of US\$1.85/t represented an annual cost savings of US\$10.8 million per year offsetting the higher capital cost for the HPGR-Ball mill circuit.

The comparative economics for the HPGR-ball mill circuit with the SABC circuit indicated a 19.6% increase in IRR and an increase in NPV (10%) of \$18.6 million. Despite the above HPGR benefits, the owners elected to install SABC that at that time was considered more conventional.

Anglo Platinum — Mogalakwena North platinum concentrator

Rule *et al.* (2008) described the new 7 million tpa Mogalakwena North concentrator incorporating the first HPGR in the platinum industry treating platreef ore. HPGR is installed after two stages of crushing and ahead of an

Table I
HPGR grinding energy—Mogalakwena North

Target grind size (μm)	300	150	106	75	45
Stage 1 HPGR energy (kWh/t)	3.3	3.3	3.3	3.3	3.3
Ball milling HPGR product (kWh/t)	16.2	25.6	32.8	57.7	53.7
Total HPGR BM route energy (kWh/t)	19.5	28.9	36.1	61.0	56.9
Stage 1 — Jaw crushing (kWh/t)	2.4	2.4	2.4	2.4	2.4
Stage 2 — HPGR (kWh/t)	0.9	0.9	0.9	0.9	0.9
Jaw + HPGR energy (kWh/t)	3.3	3.3	3.3	3.3	3.3
Ball milling for conventional product (kWh/t)	23.6	33.7	40.0	63.0	70.0
Total conventional route energy (kWh/t)	26.9	37.0	43.3	66.3	73.3
Net energy saving for HPGR route (kWh/t)	7.4	8.1	7.2	5.3	16.4
Energy saving (%)	27.6	22.0	16.7	8.0	22.3
Average energy saving (%)	<		19		>

Source: Rule *et al.* (2008)

MF2 ball milling and flotation circuit. HPGR was selected based on tests that invnution having high specific throughput rates, creating a high percentage of fines (29–33% passing 250 µm in final product with a specific energy consumption of between 1.2 and 1.6 kWh/t at an optimum specific grinding force between 3 and 4 N/mm². Polysius' Atwal® wear index also indicated the lowest wear rate encountered to date by Polysius for a 'hard rock' ore. This is particularly interesting since Platreef ore is considered to be a medium-to high wear rate ore in conventional comminution circuits and in conventional abrasion tests.

JKMRC conducted Labwal batch tests with the aim of quantifying the potential energy benefit of HPGR and developing a simulation model for Platreef ores.

Positive results in lab scale tests paved the way for large semi-commercial scale HPGR testing over a six-month period at site in 2004–5. The aim of the 75 tph (fresh feed) test was to obtain an accurate measure of actual wear rate, reliability, and operating cost and at the same time to introduce HPGR to the operating and maintenance personnel. This test demonstrated conclusively that low roll wear and a favourable subsequent ball mill particle size distribution was achievable on the hard and variable ore types mined at PPL and the PPRust North pits.

The decision in favour of HPGR technology at Mogalakwena was enabled by:

- The fine HPGR product particle size distribution
- Reduction of energy requirement for the overall circuit by HPGR installation
- Low HPGR wear rate
- Potential for metallurgical improvements
- Acceptance of HPGR by the operating and maintenance staff
- 96% availability of the HPGR during the six-month test period
- Ore characteristics and plant feed variability were major risks for AG/SAG.

The Mogalakwena North flow sheet consists of two-stage conventional crushing feeding a single PC 22/16-8 with 2 @ 2 800 kW motors; feeding two 26 ft diameter ball mills each with 17.5 MW gearless drives in an MF2 flowsheet.

The single 345 tonne Mogalakwena HPGR machine has 2 200mm roll diameter, and a roll length of 1600 mm, installed power of 5 600 kW (2@ 2 800 kW). The machine is designed for 2 160 tph throughput at a feed size < 65 mm and product size < 8 mm (50% < 1 mm)

The HPGR unit at Mogalakwena North demonstrated an immediate enhanced downstream circuit stability. The HPGR comminution circuit immediately provided a very steady particle size distribution despite variations in the quality of feed to the plant. Rule *et al.* (2008) listed a few initial operating and design challenges identified during commissioning that were rapidly overcome mainly by ensuring that the HPGR was choke fed.

Cleveland-Cliffs Empire concentrator, Michigan

Dowling *et al.* (2001) and McIvor *et al.* (2001) described the installation of the HPGR machine commissioned in 1997 to treat AG mill pebbles. Cleveland-Cliffs' Empire iron ore concentrator's HPGR experience included significant ore throughput improvement benefits as well as a reduction in specific energy consumption. This was

achieved by retrofitting HPGR to treat critical size material. The greatest improvements were reportedly achieved on higher work index ores. In 1997 and 2001 the price of energy was still low and apparently industry at that time was more focused on improving throughput than on energy saving aspects. The authors mentioned energy savings only in passing.

The successful application of HPGR at Cleveland-Cliffs Empire mine is important because HPGR synergies with AG mills are a beckoning opportunity that remains to be exploited further both in iron ore treatment and also in base metals and platinum ore treatment.

Cyprus Sierrita Copper-Molybdenum mine, Sierrita, AZ — HPGR demonstration

The HPGR demonstration plant installed at Sierrita in the mid-1990s according to Patzelt *et al.* (2001) demonstrated that throughput rates in excess of 2 000 tph could be achieved in a single HPGR unit generating a product with 25–40% < 1 mm and 15–25% < 250 µm in a single pass through a working gap of 50 mm. The energy required to achieve this product fineness varied from 1.8 to 2.2 kWh/t

Thompson *et al.* (1996) have described the HPGR installation at Sierrita in detail. Wear abatement technology challenges identified at Sierrita in the 1990s have been addressed.

Freeport McMoRan Cerro Verde Copper concentrator, Peru

Four HPGR machines with 2.4m diameter x 1.6m rolls each connected to two @ 2 500 kW drives (5 000 kW per HPGR) with variable speed drives were selected ahead of four shell-supported 24 ft diameter ball mills each with a 12 MW wrap around motor. This 108 000 tpd design capacity plant has been operating successfully since 2008.

Vanderbeek *et al.* (2006) presented on the selection and implementation of HPGR at Cerro Verde copper mine in southern Peru. Grinding tests indicated that to achieve the optimum float feed size, 38 000 kW on SAG plus 38,000 kW in Ball Mills would be required. The original feasibility study called for two 40 ft x 22 ft SAG mills plus four 24 ft x 35 ft ball mills with 12 MW drives plus three MP1000 crushers for pebble crushing.

The comparable HPGR-ball mill circuit required four @ 2.4 MW x 1.6 m HPGRs each fitted with two @ 2.5 MW variable speed motors, i.e. 5 000 kW installed power per HPGR machine, for a total of 20 000 kW installed HPGR power. The HPGR-mill circuit required four ball mills identical to those required for the SABC circuit.

Extensive HPGR test work by Phelps Dodge (now FMI) determined that:

- The HPGR specific energy increased linearly with increasing press force.
- HPGR product fineness is strongly influenced by press force. Higher pressures result in more fines
- As the press force was increased from 3.5 N/mm² to 4.0 N/mm² a point of diminishing returns was reached beyond which the product fineness benefits were negligible.
- Increase in moisture levels from 2% to 4% resulted in 5% reduction in specific throughput and 20% increase in specific energy required by the HPGRs
- Variable speed HPGR machines provided operating flexibility benefits.

- Harder ores exhibited a slight reduction in specific throughput and generated a coarser product than softer ores.
- Specific throughput of HPGR increased 10% under locked cycle testing because the composite feed size to HPGR became finer as a consequence of recycling discharge screen oversize material. Locked cycle specific energy decreased 10% compared with open circuit HPGR specific energy.
- Specific throughput of 230–250 t-s/m³-h would be required for HPGR
- Specific energy consumption would be 1.7–2.0 kWh/t
- Press force would be 3.5–4.0 N/mm²
- The same ball mills (four 24 ft x 35 ft with 12 MW motors) would be required following HPGR as following SAG mills
- Even with 2 250 kW installed for dust collection in the HPGR circuits versus zero for the SAG mill circuit, operating power for the entire HPGR-Ball mill circuit was 72 487 kW vs. 89 339 kW for the SABC circuit. The incremental specific power cost savings was estimated to be \$0.144 per t in favour of HPGR.
- Balls and liners for the SABC circuit were estimated to cost \$0.505/t vs. \$0.359/t for the HPGR-BM circuit, giving the HPGR-BM circuit an advantage of \$0.209/t.
- Total comminution costs for HPGR-BM was estimated at \$1.326/t vs. \$1.685/t for the SABC circuit giving HPGR a cost advantage of \$0.369/t—a significant amount of money for a plant operating at over 108 000 tonnes per day.

Vanderbeek *et al.* (2006) estimated that the cost benefit of HPGR-BM over SABC would break down as shown in Table II.

Vanderbeek *et al.* (2006) found that the Cerro Verde HPGR-Ball Mill circuit would have a total specific energy advantage over SABC of 15.9 kWh/t versus 20.1 kWh/t. Specific energy would be distributed as shown in Table III.

Vanderbeek *et al.* (2006) concluded that the significant reduction in operating costs of the HPGR-Ball Mill option more than justified the higher capital cost compared with a comminution SABC flowsheet. Shorter leadtime, minimization of the construction schedule and the amount of time required for production rates to ramp up to design levels as well as an evaluation of risks associated with HPGR versus 40-ft diameter SAG mills also weighed in favour of selecting HPGR after a detailed review of many HPGR operations worldwide. The internal rate of return for the whole project with HPGR was 1–1/2% higher compared with SABC.

Imperial Metals Inc—Mount polley expansion project

The existing crushing plant consists of a primary gyratory crusher followed by one secondary cone crusher and three short-head tertiary crushers feeding two parallel primary grinding lines each consisting of a 4.145 m x 5.486 m rod mill in open-circuit followed by a 4.145 m x 8.54 m ball mill in closed circuit. The primary grinding product of both circuits was combined and fed to three pebble mills (two 5.36 m x 7.32 m and one 5.06 m x 9.75 m). The conclusions of the scoping study by Wardrop Engineering as described by Anguelov *et al.* (2008) was that the 50% expansion could be achieved by converting the existing rod mills to ball mills and by installing two HPGR units in front of the mills.

The trade-off study by Wardrop Engineering indicated a two-year investment payback for the expansion project.

The HPGR product was designed to be minus 7.5 mm with incremental power cost of US\$0.13/t and wear consumables cost of US\$ 0.55/tonne.

Newcrest—New Celebration gold mine

Dunne *et al.* (1996) reported on the gold leach recovery achieved for various size coarse particles at New Celebration, comparing HPGR vs. conventional comminution. The results are self-evident in favour of HPGR as shown in Table IV.

Newmont Mining—Boddington Gold Mine, Western Australia

Boddington Gold Mine is being commissioned at the time of writing and no doubt more up-to-date definitive information will soon be published. Early information on the Boddington considerations leading up to the selection of HPGR is useful.

Process development in the late 1990s for the huge low-grade Boddington gold mine led to the realization for the first time that HPGR could not only enhance SAG mill performance, but could beneficially replace SAG mills from the SAG-ball mill circuit.

Patzelt *et al.* (2001) showed that ‘The installation of HPGRs is now being considered for various new gold projects. The direction that most of the investigations has taken was to shift more grinding work away from the SAG mill to the HPGR and not to use the machine only as a pebble crusher. In the Boddington Project, the HPGR was initially used in parallel to the SAG mill to maximize the

Table II
HPGR-BM cost advantage over SABC—Cerro Verde

Power	\$0.144 /t
Grinding media	\$0.215/t
Mill and crusher liners	(\$ 0.009/t)
Operating and repair supplies	(\$0.022/t)
Operating and repair labour	(\$0.006/t)
Delta operating costs	\$0.368/t

Source: Vanderbeek *et al.* (2006)

Table III
Comminution circuit specific energy—Cerro Verde

Category	SABC	HPGR
Size reduction equipment	17.8	11.8 kWh/t
Ancillary equipment	2.3	4.1 kWh/t
Total comminution circuit	20.1	15.9 kWh/t

Source: Vanderbeek *et al.* (2006)

Table IV
HPGR vs. conventional comminution—New Celebration

Particle size P80 (µm)	HPGR		Conventional	
	Residue (g/t)	Gold recovery(%)	Residue (g/t)	Gold recovery(%)
4000	0.10	79.0	0.22	57.9
425	0.12	78.3	0.17	69.0
325	0.11	2.1	0.13	73.1

Source: Dunne *et al.* (1996)

circuit throughput. The results showed that even using the largest SAG mill (40') would have limited the plant throughput to the extent that the desired throughput could not be reached.'

Parker *et al.* (2001) presented a summary of the decision making process that resulted in the selection of HPGR technology instead of the more conventional SABC and ABC circuit for the 25 Mtpa Boddington Expansion project. The huge Boddington ore reserve comprises 405 million tonnes with an average grade of 0.91 g Au/t and 0.12% Cu.

Boddington ore is a combination of competent diorite and andesite with typical ball mill work indices of 14 to 17 kWh/t and rod mill work indices of 21 to 26 kWh/t and unconfined compressive strengths of 150 to 200 MPa. The Boddington feasibility study was based on extensive SAG and HPGR tests performed from 1995 through 2002.

Initially HPGR was evaluated as a precrushing device to assist the SABC circuit. However, it soon became apparent that HPGR benefits would be much greater if two HPGRs were to be installed in lieu of the SAG mill, ahead of three large ball mills.

Parker *et al.* (2001) showed the following specific power comparison for three comminution circuit options considered for Boddington: See Table V.

Risk Assessment is reported as having been a major factor in the Boddington team's selection of HPGR in lieu of 40 ft SAG mills. The risk of treating a highly variable hard ore in a 40 ft diameter SAG mill was considered greater than employing crushers and HPGR for the first time.

Indicative comminution circuit capital and operating costs for Boddington were reported by Parker *et al.* See Table VI.

Clearly, the specific power required to treat Boddington ore is lower when HPGR is substituted for SAG mills. It is known that the owners scrutinized the extra power

requirements for ancillaries required for the HPGR—Ball mill circuit, e.g. extra screens, conveyors and dust control devices but the economics clearly favoured HPGR over SAG for this ore.

Northam platinum UG2 plant

Rule, Minnaar & Sauermann (2008) describe the HPGR installed at Northam UG2 plant. This was the first installation in a PGM UG2 concentrator. The HPGR retrofit met its goals namely to increase plant capacity (from 75,000 tpm to 100,000 tpm) while reducing operating costs and energy consumption, improving PGM recovery and reducing the chrome levels in the final concentrate.

The 950 mm diameter x 650 mm long HPGR (Polycor® 09/06-0) fitted with 2 @ 200 kW drives is designed to treat 160–200 tph of <32 mm UG2 feed and achieves a product size of 75% passing 1 mm feed to the ball mill.

Rule *et al.* (2008) found that total energy consumption is 20–30% lower than the original plant for the grinds achieved. The HPGR-Ball Mill retrofitted comminution plant achieved 42% <75 µm grind. This is a 100% improvement on the best case in the previous plant of 22% < 75 µm Recovery of PGM improved 4% to 84% while reducing the chrome content in the final flotation concentrate to 1.9% Cr₂O₃. The HPGR retrofit saved R600,000 per month for rod mill rods.

The HPGR at Northam is very important as this is the first application of HPGR in conjunction with flash flotation...There are surely benefits to recovering liberated base metal sulphides containing PGM's by flash flotation rather than feeding already liberated base metal sulphides to a ball mill. Ball mills have to be regarded as a destructor of sulphide mineral grains and recovery of liberated sulphide minerals ahead of the ball mill would surely have beneficial effects on flotation recovery.

Table V
Specific power comparison—Boddington Gold Mine

	SABC	Pre-Crush/SABC	HPGR/Ball
Throughput (t/h)	1440	2600	3000
Primary Crusher	60 x 110	60 x 110	60 x 110
Secondary Crusher	–	MP1000	2MP 1000s
HPGR Power (MW)	–	2.0–3.3	8
SAG Mill	12.2 m dia x 6.1 m 20 MW	12.2 m dia x 7.3 m 24 MW	–
Pebble crusher	2 @ MP1000's	2 MP 1000's	–
Ball mills – number	Two	Two	Three
Ball mills – size	10 MW	7.9 m dia x 14.4 m	16 MW
Operating Power (approx MW)	33.3	51–55	43–53
Circuit specific power kWh/t	23.1	20.2–21.2	18

Source: Parker *et al.* (2001)

Table VI
Indicative comminution circuit capital and operating costs—Boddington Gold Mine

Parameter	Units	SABC	Pre-crush/SABC	HPGR/Ball Mill
Annual throughput	Mt/a	11.2	20.8	25.0
Capital cost estimate	A\$/tpa	12.34	7.43	5.75
Operating cost estimate	A\$/t	4.18	3.32	2.95

Source: Parker *et al.* (2001)

Pacific Booker Minerals Inc. – Morrison Copper project, B.C.

Designed for 30 000 tpd (i.e. 11 million tpa) the original flowsheet was SAG grinding and flotation to produce 155 000 tonnes of concentrates per year containing copper, gold and molybdenum.

Anguelov *et al.* (2008) describe HPGR pilot test work by Polysius on drill core material. Closed circuit screening was simulated with a 6 mm screen (actual cut at 5 mm). Test results indicated a potential energy savings of 14% at p80 of 200 μm and 12% at 90 μm .

SGS Lakefield conducted additional laboratory work to investigate the effect of HPGR comminution on metallurgical performance. HPGR product required less grinding time to produce an equivalent grind size (suggesting a reduction in BWI following HPGR) but flotation recoveries were equivalent. Subsequent locked cycle tests on both HPGR-ball mill and SA-ball mill product showed that there would be no difference in grade or recovery of the final concentrate.

The Wardrop Engineering HPGR trade-off study described by Anguelov *et al.* (2008) would result in a power cost savings from US\$0.63/t for SAG to US\$0.56/t for HPGR whereas wear part consumables would be decreased from US\$2.03/t for SAG-Ball Mills to US\$1.47/t for HPGR-Ball mills.

Seabridge Gold – Courageous Lake Gold Project, Northwest Territories

According to Anguelov *et al.* (2008) the Courageous Lake project expects to treat 25 000 tpd gold ore. The Wardrop Engineering trade-off study employing HPGR in the place of SAG showed a reduction in overall comminution costs by more than 25%. Increasing the availability of HPGR to 96% would increase plant capacity by 400 000 tonnes per year. Power cost would be reduced from US\$3.59/t for SAG-BM to \$2.47/tonne and the cost of grinding media and mill/crusher liners would be reduced from US\$1.39/tonne for the SAG-BM circuit to US\$1.15/tonne to achieve a minus 3.0 mm HPGR product and a minus 125 μm ball mill product.

Vista Gold, Mt. Todd gold mine, northern territory, Australia

Mt. Todd gold project in the NT of Australia is being reborn. Pegasus Gold installed VSI crushers in the project's first life in the 1990s when Mt. Todd fell victim of weakening gold prices and other challenges. HPGR had been tested and shown excellent results at that time, but wear abatement risks were at that time still considered to be 'uncharted waters' for hard abrasive ores.

Van den Meer (1997) described a 30 000 tonne pilot plant demonstration of HPGR on a tough, abrasive diorite ore with the objective to grind from 90% <1.5' to about 80% <105 μm . The HPGR process route clearly demonstrated a reduction in ball milling power consumption of between 2.0 and 2.6 kWh/t compared to conventional crushing and ball milling techniques. In this case an indicative comparison made against other process routes (including SAG and 2-stage-crushing) for grinding down to P80 = 90 μm , suggested an overall power saving of between 1 kWh/t and 8kWh/t by the HPGR-ball milling process route.

Van den Meer (1997) goes on to state, 'A potential operating cost savings of US\$0.80/t was estimated for the HPGR route. Of which half came from the reduced power requirements and half from the reduction in grinding media cost for this abrasive ore...'

.... In addition to the above plant trials, calculation of leach recoveries during the trials based on head-tails analysis indicated an increase in recovery of 2–3 %'.

Vista Gold (2008) reported in a press release that based on more recent HPGR tests performed by Polysius Corp. in Germany and reviewed by Deepak Malhotra of Resource Development Inc., comminution of Mt Todd ore by two-stage crushing followed by HPGR followed by ball milling would save 9.5 kWh/t compared with a SAG-Ball mill circuit. At an estimated power cost of US\$0.12/kWh this represents US\$1.14 per tonne in energy savings alone.

Retrofitting HPGR for treatment of harder ores as open-pit mines go deeper

At least one mining company has selected three-stage crushing ahead of ball milling for the early years of treating softer near-surface open pit ores. Space has been left in the plant layout to retrofit HPGR at a later stage to maintain production throughput as the mine gets deeper and ores get harder.

Copper slag treatment

2007 work compared the energy efficiency of HPGR versus ball milling in the treatment of copper smelter slag. It was found that HPGR-Ball milling is more 12% energy-efficient than Ball milling in reaching 80% minus 150 μm product. However, if the HPGR was installed in closed circuit at steady state with a 1.7 mm screen, then the HPGR-Ball mill circuit energy efficiency improvement increased to around 20%.

Energy efficiency improvement of an HPGR in closed circuit with a screen over an HPGR in open circuit would be expected based on the observations by Johnson *et al.* (1995).

Process development frontiers

Heap and dump leaching according to Marsden (2008) is significantly more energy efficient than processes that involve crushing and grinding. Heap and run-of-mine dump leaching, however, have thus far resulted in lower recoveries of gold and/or copper than can be achieved using more intensive processes such as grinding and agitated leaching or grinding-flotation and smelting or hydrometallurgical treatment of concentrates.

HPGR treatment of ores has been shown to frequently result in improved gold or copper leach recoveries. Randol International Ltd has conceptualized a processing system whereby HPGR in conjunction with a novel vat leaching technology can be applied in the treatment of copper, uranium or gold/silver ores to further enhance leach rates and leach recoveries, but consuming much less energy and water than conventional agitated leach processes.

At an industry workshop on 3 April 2008 at Mintek to solicit industry support for National Research Foundation funding of research 'towards a more energy-efficient concentrator' flowsheet.

Three comminution circuits were proposed, each of which employed HPGR in a different way:

- HPGR integrated with ROM-ball or AG/SAG mill
- Ball mill circuit with HPGR employed as a tertiary crusher
- Two HPGRs in series followed by three stages of fine-grinding mills in series – a circuit that avoids tumbling mills altogether.

Von Michaelis (2001, 2003) described additional frontiers for the treatment of oxide gold-copper ores and also bio-oxidation in heaps for the treatment of sulfide copper ores employing Geo-Biotics' GEOCOAT® process. The application of HPGR to generate micro-fractures in ores and improved particle size distributions for more engineered heap or vat leaching e.g. employing the Innovat® process can be expected to result in better leach recoveries while consuming less energy and water than conventional processes.

Randol has conceptualized the application of HPGR to improve flotation and/or leaching recoveries of gold and uranium in the retreatment of tailings by exposing new mineral surfaces for flotation and introducing micro-fractures to enhance leach recovery.

Conceptually, applying HPGR following energy-efficient microwave pre-treatment to weaken ore or introduce stresses along grain boundaries should be synergistic. This concept could be applied to DMS or sorted concentrates and followed by flash flotation and gravity concentration to recover liberated sulphide and/or gold particles ahead of subsequent ball milling.

Definitions

Specific energy—Input (kWh/t) = net power (kW)/throughput (dry t/h)

Specific energy—input is the net power draw per unit of throughput. Typical operating values are in the range of 1–3 kWh/t. In general, a given ore will absorb energy to a point beyond which little useful work is achieved.

Specific pressure—(N/mm²) = Force (N) / D (mm) × L (mm)

Specific pressure—is the force (Newtons) divided by the apparent (or projected) area of the roll – that is the product of the roll diameter and length. Typical operating values are in the range of 1–4.5 N/mm².

Testing representative ore samples

Energy consumption comparisons of various comminution circuits are based on testing the specific energy requirements as measured by test work performed on ore samples.

For new projects, the only samples available are often near-surface material that may not be truly representative of the ore deposit as a whole.

In other cases the only material available for test work may be drill core. It has been pointed out that diamond drill core may also not truly represent ore from the same deposit mined by blasting as the latter may be weakened by fracturing that does not occur in drill-core.

Daniel (2008) employed a piston-die to test the response of various ores to piston-die compression tests. He concluded: 'The output of such tests, product size distribution, and comminution energy may be used to

predict the performance of a laboratory scale HPGR, which in turn may be used to predict the performance of an industrial scale HPGR'.'The piston-die tests reconfirm the manufacturers' rule of thumb that energy input should range between 1–5 kWh/t for all ores treated in HPGR units.The piston-die and ball mill comminution energy comparison tests confirm that less energy is used during particle bed comminution to produce finer products. Hence inter-particle comminution is more energy efficient than single impact breakage processes found in ball mills.

Conclusions

- HPGR followed by ball milling typically saves 10–25% of comminution specific energy compared with SAG, AG or SABC circuits.
- Energy efficiency of HPGR is ore-specific. In general, the harder the ore, the greater the energy savings is likely to be.
- Conventional Bond Work Index measurements conducted on HPGR product do not reflect the larger amount of fines generated by HPGR.
- Innovative flow sheets that employ HPGR in conjunction with synergistic technology can save much more energy overall, e.g. HPGR treating ore sorting or DMS concentrate and/or HPGR followed by flash flotation.
- Wear of HPGR parts is miniscule compared with the amount of steel lost due to SAG mill liner and media wear. If the energy required to produce the steel wear parts lost during comminution is factored in, HPGR is even more energy efficient than SAG mills.
- Heap and vat leaching are more energy efficient (and more water efficient) ways to produce metal (per lb Cu or per oz Au). However, for the treatment of higher-grade ores, the lower recovery of heap and vat leaching makes these processes less efficient. Tests indicate that HPGR-treated ores yield better and faster gold and copper heap leach recoveries.
- HPGR is being tested in closed circuit with fine screening. This promises to greatly enhance the energy efficiency of HPGR. A new generation of excellent fine screening equipment has been developed. Screen classifying allows material to be classified by size rather than density.
- Frontier research such as HPGR following microwave pretreatment to weaken ore along grain boundaries offers still greater energy benefits of HPGR in the future especially if combined with DMS ahead of the microwave-HPGR application and followed by flash flotation and/or gravity to recover sulphides and gold ahead of ball milling.

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