

# **MICROCRACKING VERSUS THE PHANTOM CYCLONE; COMPARING SAG MILLS AND HPGR ON A CONSISTENT BASIS**

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## **ABSTRACT**

*Both Semi-Autogenous Grinding (SAG) mills and High Pressure Grinding Rolls (HPGRs) create more product fines than cone crushers or rod mills. Many recent HPGR papers claim benefits of these additional fines (often referred to as “microcracking”) when comparing to “standard” circuits involving cone crushers. An analogous effect is observed in SAG milling, where pilot plants and operations demonstrate more fines being produced than the same “standard” circuits. Some SAG milling designers employ a modelling technique called a “phantom cyclone” to “correct” the SAG mill product to make it match a “standard” ball mill feed (molienda unitaria) particle size distribution, which has the net effect of reducing the power demand of the secondary ball mills.*

*So how do SAG mills and HPGRs compare when treated to the same modelling technique? This paper presents a case study of one Chilean ore that underwent both HPGR and SAG mill bench-scale testwork. Interpretation of the HPGR “microcracking” was conducted using the same phantom cyclone approach used for a SAG mill design. By applying the same modelling technique to both technologies, it is possible to make a proper comparison of the overall circuit energy requirements. To make a financial choice between the two technologies, it was necessary to characterize all the ancillary equipment required for HPGR to properly account for the capital costs associated with the larger plant footprint, the circulating loads and the wear associated with the HPGR.*

## **INTRODUCTION**

In his Third Theory of Comminution, Fred Bond developed work index relationships expecting that any unscalped comminution process would produce a predictable particle size distribution with a slope of  $\frac{1}{2}$  [1]. Since the Third Theory was published, new equipment has been adopted by the industry that doesn't follow the particle size distribution assumed by Bond. This causes calculation problems when combining a “new” piece of process equipment, such as a Semi-Autogenous Grinding (SAG) mill or a High Pressure Grinding Rolls (HPGRs) ahead of an “old” piece of process equipment, such as a ball mill that is modelled using Bond work indices.

Techniques have been developed to accommodate the different size distributions being fed to a ball mill downstream of a SAG mill or HPGR. The “phantom cyclone” is a technique commonly used to remove “extra” fines created by a SAG mill that result in the operating work index of a ball mill to fall below its laboratory-determined work index value [2]. The concept of “micro-cracking” is commonly applied when considering ball mill feed from HPGRs where the operating work index of ball mills is also judged to fall below the laboratory-determined work index value [3,4].

Based on the hypothesis that the microcracking in an HPGR is a manifestation of the same mechanism that generates additional fines in a SAG mill (additional fines versus the Bond assumption), the authors have characterized both an HPGR and a SAG mill circuit using the phantom cyclone approach. A comparison of the overall circuit grinding energy requirements is then performed on both circuits and financial comparisons are made. This characterisation is then compared to published data to see if a phantom cyclone model produces results consistent with observed HPGR operation.

## **METHOD**

### **Laboratory testing**

Laboratory testing of Mantoverde samples was undertaken at the SGS laboratories in Santiago, Chile and Toronto, Canada. The SAG mill characterisation consisted of Bond work index tests for low-energy impact crushing, rod milling and ball milling conducted on several samples from four UGMs (lithologies). The HPGR characterisation consisted of several 2 kg Minnovex Static Pressure Tests (SPT) on two UGMs. The SPT test does not produce an estimate of roll wear. No ball mill work index tests were attempted on SPT product due to insufficient sample size.

### **Flowsheets**

The SAG mill circuit is a conventional SABC circuit with SAG screen undersize feeding the ball mill circuit pumpbox. The SAG feed is primary crusher product; an  $F_{80}$  of 150 mm. The circuit product size  $P_{80}$  (cyclone overflow) is 135  $\mu\text{m}$ .

Two HPGR circuits were considered: first using two stages of conventional crushing feeding a tertiary HPGR in closed circuit with a dry screen; second using three stages of conventional crushing feeding a quaternary HPGR in closed circuit with a dry screen. A literature review of HPGR abrasion estimates shows that coarser feed to a tertiary HPGR circuit will result in a higher degree of roll wear versus the finer feed of a quaternary HPGR circuit.

### **The “Phantom Cyclone”**

Where large quantities of fines are present in the feed to the ball mill circuit, the grinding circuit should first pass the ball mill feed to the hydrocyclone ahead of the ball mill [5]. The hydrocyclone removes a portion of the finished product from the ball mill circuit without incurring any ball mill energy, effectively bypassing fines past the ball mill circuit. The effect of this by-pass of fines can be modelled using phantom cyclone ahead of the ball mill circuit (see Figure 1). Using a hydrocyclone model, such as the one described by Arterburn [6] the quantity of bypassed fines can be determined and a synthetic ball mill circuit feed that corresponds to the Bond particle size distribution is created as the phantom cyclone underflow.

Any ball mill work operating index calculations are performed using the throughput and particle sizes of the phantom cyclone underflow. The flow bypassing the phantom cyclone overflow consumes no energy in the ball mill circuit and is excluded from Bond work index calculations.

The method used for characterisation of the SAG circuit is the “ $E_{ssbm}$ ” formulae described by Barratt [2, 7].

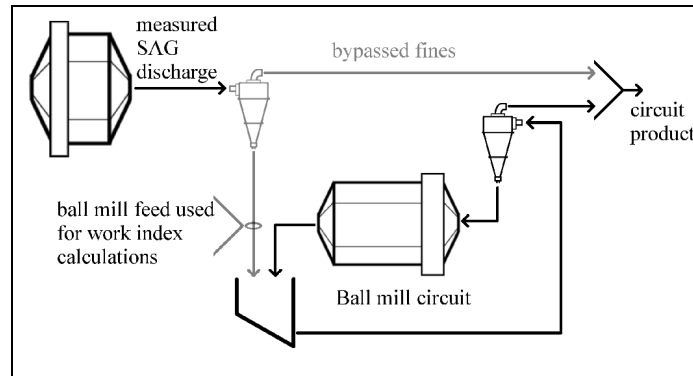


Figure 1: Conceptual Flow Sheet for a SAG Mill Phantom Cyclone Calculation

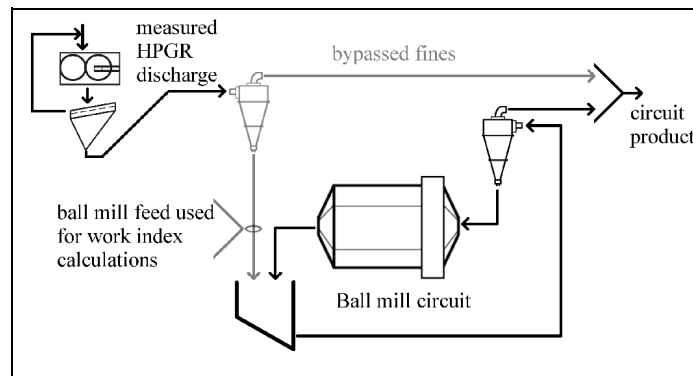


Figure 2: Conceptual Flow Sheet for a HPGR Phantom Cyclone Calculation

The same concept is applied for HPGR, except that the HPGR circuit product (screen undersize) is used in place of the SAG discharge (see Figure 2). Though the HPGR circuit product may be fed directly to the ball mill or to the ball mill discharge sump [8], it is assumed that the effect on the ball mill circuit power draw is the same. The authors are not aware that this assumption has been tested in operation, and it is possible that the forward closed-circuit ball mill (where the HPGR product directly feeds the ball mill) will see less reduction in grinding energy than the reverse closed-circuit operation (where the HPGR product goes to the ball mill discharge sump) as there is no chance for fines to bypass the ball mill.

The operating work index values generated by the phantom cyclone technique is given in Table 1. The difference in HPGR operating work index versus the laboratory for UGM 1 and 4 are in line with literature, but UGM 2 and 3 show negligible difference. The lack of a reduction is probably a function of the nature of the ore (both are breccia) as DJB Consultants, Inc. has observed a similar result on heterogeneous ore on another project. The SAG mill shows a larger reduction in ball mill operating work index versus the laboratory than the HPGR on all samples.

Table 1: Operating ball mill work index values & laboratory work index

UGM	Average ball mill work index, metric			Wi:Wi <sub>o</sub> ratio		Description
	Laboratory, Wi	HPGR, Wi <sub>o</sub>	SAG, Wi <sub>o</sub>	HPGR	SAG	
1	12.8	11.3	10.9	87.9%	84.5%	Primary copper + magnetite
2	16.8	17.0	15.7	101.7%	93.7%	Breccia
3	14.4	14.4	12.4	100.2%	85.9%	Breccia
4	15.3	13.9	13.6	90.8%	88.9%	Secondary copper

## OPERATING COSTS

Overall circuit operating costs are presented in Table 2. All values are 2009 US dollars.

Table 2: Operating Costs

	SAG/Ball	Quaternary HPGR
Power: at US\$ 0.089/kWh	\$1.34/tonne	\$1.20/tonne
Steel: mill liners, balls, roll surfacing	\$0.74/tonne	\$1.15/tonne
Labour, maintenance & other	\$2.12/tonne	\$2.12/tonne
<b>Total operating cost</b>	<b>\$4.18/tonne</b>	<b>\$4.45/tonne</b>

At a milling rate of ten million tonnes per year, the annual cost difference between the two flowsheets is \$2.8 million.

## Overall circuit specific power consumption

Specific energy consumption for the entire grinding circuit from primary crusher product to 135 µm cyclone overflow was determined for both the quaternary HPGR circuit and the SAG circuit. Plotting and adding the points in the data set produces a clear reduction in energy across the range of hardness in the data set, per Figure 3. The reduction is between 10% and 20% of total energy, which is in line with other published data [9]. Even the breccia ore types (UGM 2 & 3) display a reduction.

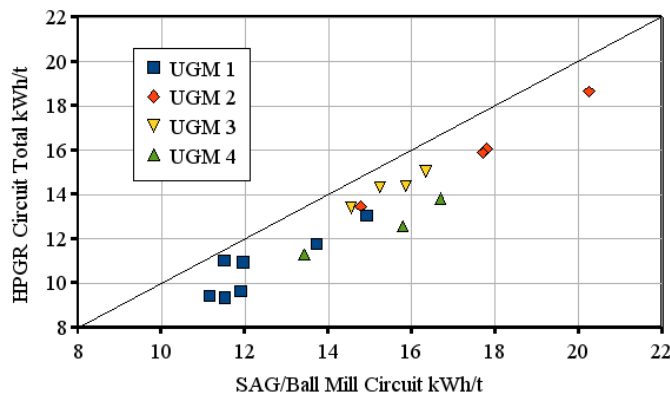


Figure 3: HPGR circuit total kWh/t versus SAG circuit total kWh/t

## Ball mill abrasion estimates

Different formulae are used to estimate the ball wear in the two different circuits. The HPGR circuit generates a ball mill feed consisting of jagged particles [10] that contribute to ball wear in a similar manner to the original Bond abrasion index for single stage ball milling.

$$\text{ball mill, ball wear } \frac{g}{kW \cdot h} = \left(0.85 \times 159 \frac{g}{kW \cdot h}\right) (Ai - 0.015)^{0.34} \quad (1)$$

$$\text{ball mill, steel liner wear } \frac{g}{kW \cdot h} = 2 \times \left(0.85 \times 11.8 \frac{g}{kW \cdot h}\right) (Ai - 0.015)^{0.3} \quad (2)$$

The SAG mill produces rounded and worn particles that result in a lower wear rate in the ball mill. Using mill surveys of a “reference” plant and ore, DJB Consultants, Inc. developed the following formulae for ball and liner wear in secondary ball mills following a SAG mill:

$$\text{ball mill, ball wear } \frac{g}{kW \cdot h} = \left(42 \frac{g}{kW \cdot h}\right) \left(\frac{Ai - 0.015}{Ai_{ref} - 0.015}\right)^{0.34} \quad (3)$$

$$\text{ball mill, steel liner wear } \frac{g}{kW \cdot h} = 2 \times \left(3.63 \frac{g}{kW \cdot h}\right) \left(\frac{Ai - 0.015}{Ai_{ref} - 0.015}\right)^{0.3} \quad (4)$$

where the reference ore has an abrasion index,  $Ai_{ref}$ , of 0.49.

These formulae predict a significantly higher ball mill steel consumption for HPGR product than for SAG mill product. The authors are only aware of one other study that makes reference to an increase in ball wear in an HPGR circuit versus a SAG circuit [8], where the simulation-based study predicted a minor (10%) difference in ball mill wear. The authors are not aware of a plant survey based comparison of ball mill steel wear.

### HPGR roll abrasion estimates

As the Static Pressure Test does not produce an estimate of HPGR roll wear, values for typical roll wear were taken from literature. The roll wear used for operating costs was US \$0.18/tonne for quaternary operation and US \$0.37/tonne for tertiary operation.

### Operating cost comparison excluding ball mill steel wear difference

The operating cost difference between the two circuits is driven by the difference in ball mill steel wear between the SAG/ball mill circuit and the crushing/HPGR/ball mill circuit. Many previous studies comparing HPGR and SAG circuit have not included this aspect of operating cost and have focused exclusively on power draw [5, 8].

“What if” the predicted difference in ball mill steel wear in the two circuits is false and there is no difference? By setting the ball mill steel wear in both circuits equal to the Bond value (the HPGR circuit estimate), Table 2 becomes Table 3:

Table 3: Operating Costs Excluding SAG/Ball Wear Benefit

	SAG/Ball	Quaternary HPGR
Power: at US\$ 0.089/kWh	\$1.34/tonne	\$1.20/tonne
Steel: mill liners, balls, roll surfacing	\$1.35/tonne	\$1.15/tonne
Labour, maintenance & other	\$2.12/tonne	\$2.12/tonne
<b>Total operating cost</b>	<b>\$4.79/tonne</b>	<b>\$4.45/tonne</b>

The operating cost advantage of the SAG/ball circuit has disappeared, and the Quaternary HPGR circuit shows a modest \$0.34/tonne cost benefit. At a milling rate of ten million tonnes per year, the annual reduction in operating costs is \$3.4 million.

## CAPITAL COSTS

The costs were estimated at a conceptual level for both comminution circuits. Scope of the estimates extends from the primary crusher through to the hydrocyclones in the ball mill plant, and includes factors for installation, ancillary process equipment, construction facilities, EPCM, owner's costs and contingency.

Table 4: Capital costs in 2009 US dollars

	<b>SAG/Ball</b>	<b>Quaternary HPGR</b>
Direct costs	\$140,400,000	\$183,700,000
Indirect costs	\$26,700,000	\$34,900,000
Owner's cost & contingency	\$46,000,000	\$60,000,000
Total capital costs	\$213,100,000	\$278,600,000

The payback for the \$65.5 million extra capital cost of the HPGR circuit is not achieved over the 16-year life of the project assuming the optimistic ball mill wear rate difference between the SAG and HPGR circuits (Table 3).

## CONCLUSIONS

In this study, the most cost-effective location for a HPGR was in a quaternary duty due to the roll wear caused by coarse feed. The higher installation cost of a fourth stage of crushing is more than offset by the improved rolls life and corresponding reduction in operating cost.

The ball mill steel wear is predicted to be higher in the HPGR circuit than in the SAG mill circuit. This higher steel consumption eliminates any cost benefit due to the HPGR circuit power consumption.

The capital cost of the SAG circuit was lower than the quaternary HPGR.

Even if the difference in ball mill steel wear between SAG and HPGR circuits is excluded, the additional capital cost associated with HPGR does not pay back over the life of the project.

Overall economics favour the SAG mill circuit for this particular ore.

## NOMENCLATURE

- A<sub>i</sub> Bond abrasion index, unitless
- A<sub>i,ref</sub> Bond abrasion index of a reference plant with a known ball & liner consumption
- F<sub>80</sub> Feed 80% passing size,  $\mu\text{m}$
- P<sub>80</sub> Product 80% passing size,  $\mu\text{m}$

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