Key Drivers of Energy and Cost Efficiency in Autogenous/ Semi-Autogenous Grinding Circuits

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ABSTRACT

In a recent publication (Bueno and Lane, 2011) the authors presented the analysis of a consolidated dataset composed by 137 autogenous/semi-autogenous grinding (AG/SAG) mill pilot trials. By comparing the measured data against theoretical specific energy consumption, the analysis indicated which circuit configurations were more or less energy efficient. However, the analysis has also indicated that the energy efficiency of each of the types of circuits vary significantly.

There are numerous factors that contribute to the variations of energy efficiency of AG/SAG mill-based circuits, such as feed size distribution, recycle ratios and ore characteristics. In view of this, the present work accesses these factors individually and discusses what may lead a particular circuit configuration to be more or less efficient in terms of energy and costs.

INTRODUCTION

This paper is a follow up on observations related to circuit efficiency made during the analysis of a database constituted by 137 AG/SAG mill pilot plant trials (Bueno and Lane, 2011). These pilot plant trials were conducted over a period of ten years and using different ores from various projects. Most tests were carried out using 1.8 m × 0.6 m (D × L) Hardinge Ical mills. Circuit configurations ranged from single-stage autogenous to SAG, ball mill and pebble crushing (SABC) circuits, as presented in Table 1.

TABLE 1

The different circuit configurations within database.

Circuit configuration	Code	No Tests
Autogenous mill followed by a ball mill	AB	5
Autogenous mill with pebble crusher followed by a ball mill	ABC	25
Semi-autogenous mill followed by ball mill	SAB	35
Semi-autogenous mill with pebble crusher followed by ball mill	SABC	47
Single-stage autogenous mill	SS/AG	6
Single-stage autogenous mill with pebble crusher	SS/AC	13
Single-stage semi-autogenous mill	SS/SAG	6
Total number of trials		137

The ores tested during these campaigns were characterised using Bond work index tests and JK Drop Weight (JKDWT) or JK Pendulum tests (Napier-Munn *et al*, 2005). Figure 1 shows the ore characterisation parameters A*b and Bond ball mill work index (BBMWi) for the ore types within this database. The different ore types were classified from 'hard' to 'soft'

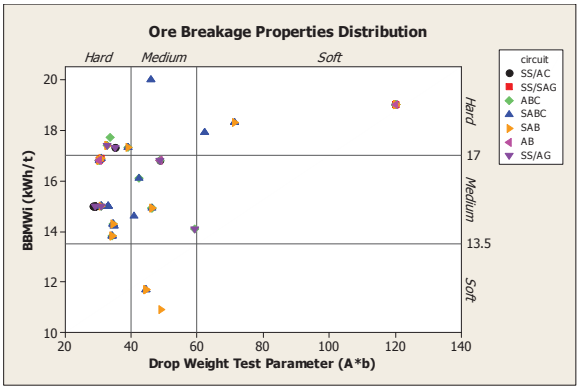

FIG 1 - Breakage characteristics of the ore types within database.

according to both their resistance to impact breakage (A*b) and grindability (BBMWi). The most common ore types tested are in the hard-medium (H-M) class. Table 2 shows which ore types were tested in each circuit.

Bueno and Lane (2011) used the methodology described in Figure 2 to calculate the energy efficiency parameter (fSAG). This relative number is calculated as the ratio between total specific power requirements for the AG/SAG and theoretical circuit (crusher, rod mill, ball mill – CRB) doing the same work (Siddall, 1999).

As the fSAG calculation is highly dependent upon the measured Bond test indices, this method is not 'foolproof', but does provide a standard for accessing and comparing the efficiency of comminution circuits. Rowland and McIvor (2008) described a similar metric that have been adopted by industry as widely used standard for quantifying industrial size reduction efficiency.

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TABLE 2
The combinations of ore types and circuits tried.

Circuit / ore	H-H	H-M	M-H	M-M	M-S	S-H	Total
AB	-	2	-	2	-	1	5
ABC	3	8	-	7	-	7	25
SAB	5	10	-	3	5	12	35
SABC	2	31	2	4	3	5	47
SS/AG	2	2	-	1	-	1	6
SS/AC	2	10	-	1	-	-	13
SS/SAG	2	-	-	-	-	4	6
Total	16	63	2	18	8	30	137

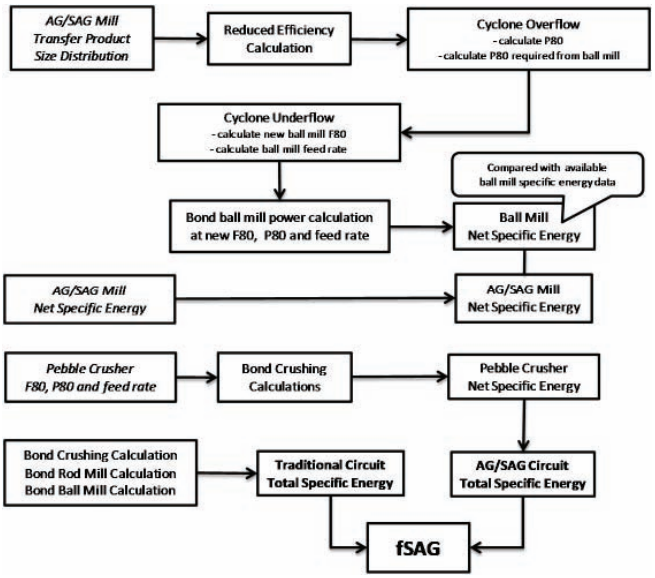

FIG 2 - Data analysis logic diagram after (Bueno and Lane, 2011).

Bueno and Lane (2011) also calculated a simplified operating cost for each trial, considering only the energy and grinding media consumptions. A cost efficiency factor (fCost) was then calculated as the ratio between the total dollar cost for the AG/SAG mill-based and traditional Bond stage crush, rod mill and ball mill circuits.

The obtained distribution of fSAG and fCost parameters for the various circuit configurations are shown in Figure 3 and Figure 4, respectively. This analysis pointed which circuit configurations were more or less energy and cost efficient,

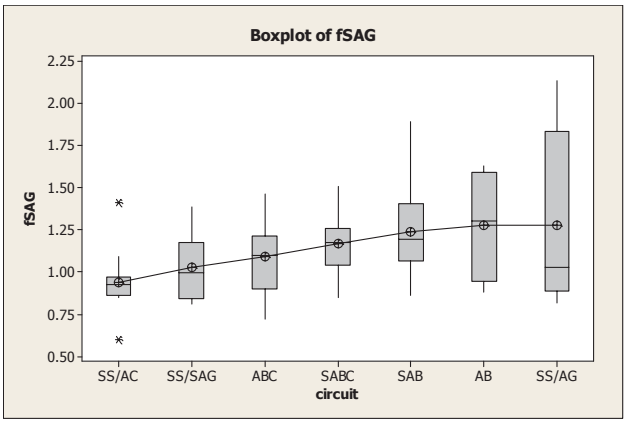

FIG 3 - Variation of energy efficiency parameter with circuit configuration.

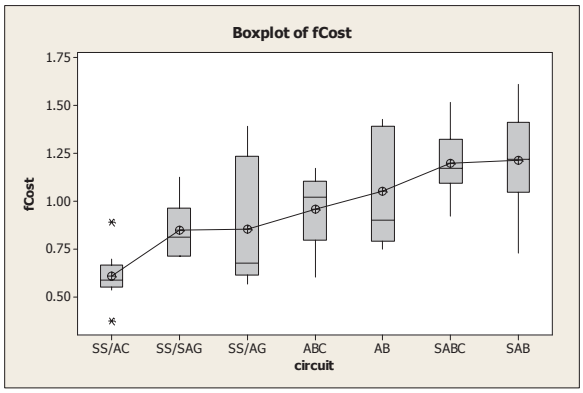

FIG 4 - Variation of cost efficiency factor with circuit configuration.

and also indicated that the efficiency of these circuits varies significantly.

There are numerous factors that contribute to the variations of efficiency of AG/SAG circuits, such as feed size distribution, recycle ratios and ore characteristics. In view of this, the present work accesses these factors individually and discusses what may lead a particular circuit configuration to be more or less efficient in terms of energy and costs. Although this analysis was completed using pilot plant test data, pilot plants are industry standard practice for evaluating different circuit configurations, resultant mill throughput and specific energy requirements (Digre, 1989).

SINGLE-STAGE CIRCUITS

Single-stage AG and SAG mill circuits can be very energy efficient, but will be accompanied by a capital cost penalty for high tonnage projects due to the need for multiple milling lines and multiple stockpile reclaim systems. Since these circuits do not have a secondary ball milling stage, they can consume little or no steel grinding media and can run with lower operating costs. Single-stage AG mill circuits are not common and the last two single-stage AG mills installed in Australia were by WMC at Kambalda and Olympic Dam in the 1990s. Single-stage SAG mill circuits are more common for small to medium sized gold projects.

Without the use of pebble crusher the performance of a single-stage AG mill circuit is extremely sensitive to ore competency. The fSAG and fCost probability distribution, plotted in Figure 5, shows that the use of balls in single-stage milling reduced the fSAG variability but shifts the fCost distribution up. Therefore, the crushing of pebbles is almost mandatory when treating ores with hard components in AG mills.

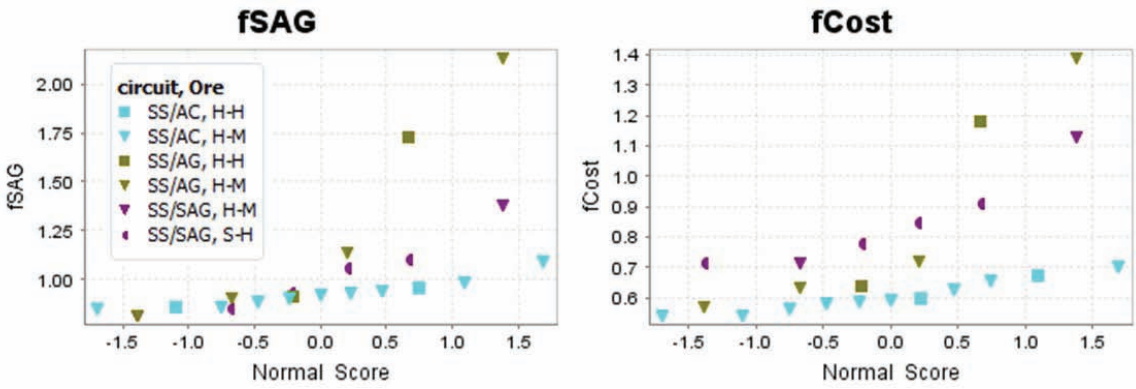

FIG 5 - Energy efficiency parameter and cost efficiency factor probability distribution for single-stage autogenous and semi-autogenous grinding circuits.

In the probability distributions graphs, presented in Figures 5 and 7, the values plotted along the X axis are in units of standard deviation. These Normal Score values represent the z-scores from a standard normal distribution (mean = 0 and a standard deviation = 1, hence N score not Z score). Data is plotted against the normal scores from that distribution.

Single-stage circuits are more efficient when grinding fine, without limiting throughput, as shown in Figure 6. This balance is difficult, because the control point is the classification and the crushing of pebbles. The recycle load should sustain a wide mill load size distribution in order to keep both impact/crushing and abrasion/attrition breakage happening. The use of balls in a SAG mill minimises the problem related to ore competency variability, but in excess it can coarsen the mill discharge, what will cause negative impacts in classification and consequently in the circuit energy and cost efficiencies.

TWO-STAGE CIRCUITS

The two-stage circuits using a primary AG or SAG mill followed by a secondary ball mill are the most common type of comminution circuit in the industry. The lower cost circuits are those with autogenous primary mills, since these do not consume steel media. However, the spreads in fSAG values are larger for AG mill circuits as they can be more sensitive to changes in feed size and ore characteristics than SAG mills, this can be seen in the fSAG and fCost probability distributions plotted in Figure 7 for AB, ABC, SAB and SABC circuits.

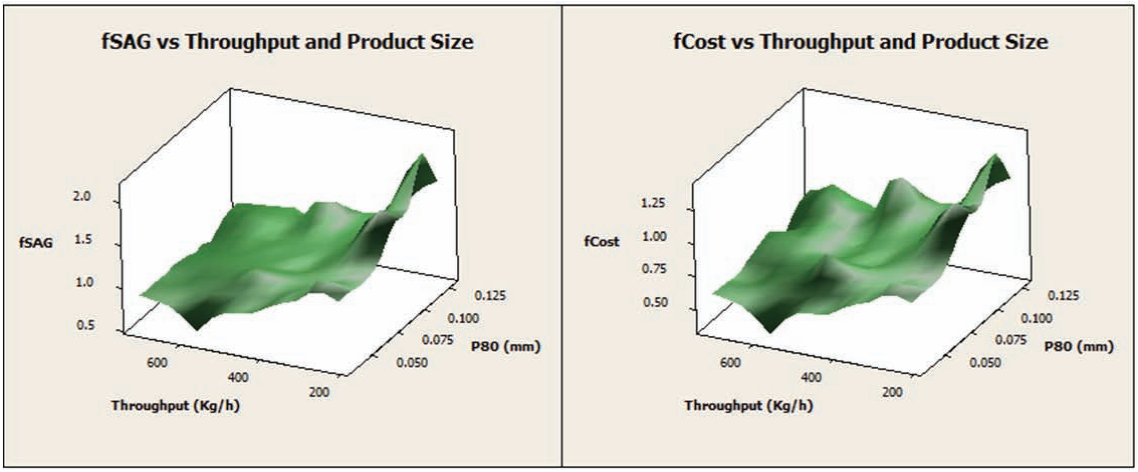

FIG 6 - The effect of throughput and P80 on energy efficiency parameter and cost efficiency factor.

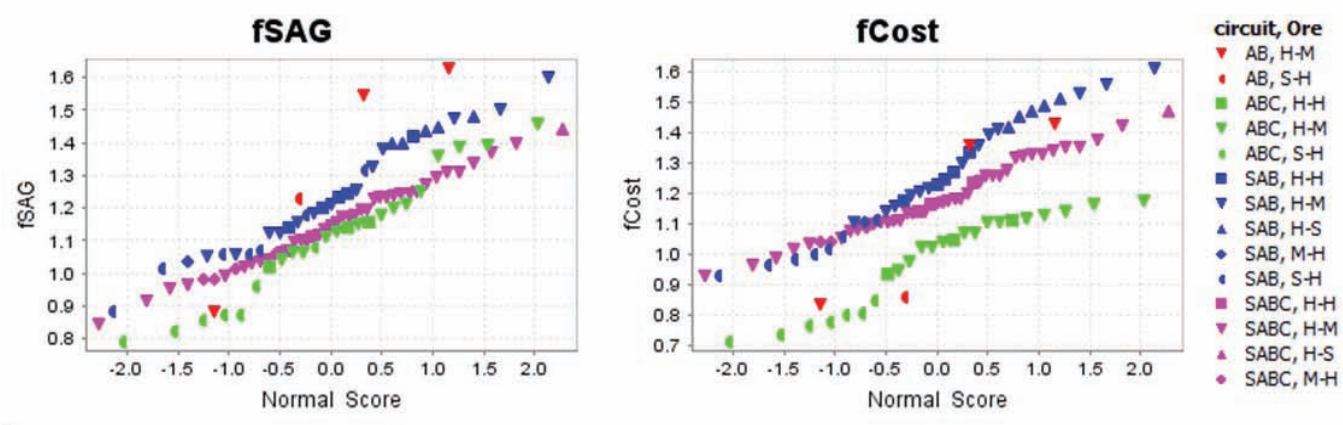

FIG 7 - Energy efficiency parameter and cost efficiency factor distribution for AB, ABC, SAB and SABC circuits.

Unless a geometallurgical or a multi-component model (Bueno *et al*, 2012) is used to access the impact of ore variability on mill performance, AG circuits are not recommended for projects where ore variability is significant. However, circuits with AG primary mills can be efficient if high throughput is achieved (when treating ores with low and moderate competency). Therefore, the use of a pebble crusher is almost mandatory when treating ores with hard components in AG mills, unless the pebbles are transferred and used as grinding media in a secondary pebble mill.

The balance between SAG and ball mill specific energy is critical feature that is related to energy and cost efficiency in any two-stage circuit. FIGURE 8 shows fSAG and fCost as a function of the AG/SAG primary mill percentage of the total specific energy consumption (Sag per cent), and it is clear that if the primary mill is drawing more than 50 per cent of the total energy consumption, the circuit is inefficient.

With very few exceptions higher throughputs that lead to coarser transfer sizes are recommended to increase circuit efficiency, as long as the downstream process is not compromised with a feed that the ball mill cannot handle. When the SAG is running at high specific energies, it produces a finer transfer product and this affects the performance of the ball mill and the whole circuit efficiency.

Pebble crushers are also beneficial in two-stage circuit because they increase throughput and consequently bringing down the cost of media and energy per processed tonne. However, when the ore competency increases, the crushing of pebbles becomes excessive and the energy and cost efficiency of ABC and SABC circuits is compromised, as shown in Figure 9.

The relationship between feed size and mill throughput is a well know effect (Morrell and W, 2001), and the use of secondary crushing or higher blast intensity to increase throughput are common practice to improve overall productivity. The current data analysis has confirmed that a reduction on feed size also improves the energy and cost efficiency of ABC and SABC circuits, as shown in Figure 10.

Semi-autogenous primary mills

The use of SAB and SABC circuits results in higher throughputs than AG mill based circuits, but these circuits consume a substantial amount of grinding media, which represents an 'embodied' energy input and therefore, has great impact on 'carbon footprint'. With the interest ineco-efficient trends and possible penalties for carbon emissions, the cost of media will increase. Figure 11 shows the distribution of this indirect energy across the different circuits.

In this study the 'embodied energy' was assumed to be 5 kWh/kg of steel based on data reported by Daniel, Lane and McLean (2010), and this indirect energy can represent more than 50 per cent of the direct energy for the SABC circuit. Figure 12 also shows that the use of higher ball loads in SAG mills can compromise the cost efficiency of these circuits, although it increases throughput.

IMPLICATIONS FOR MILL OPERATORS

Mill operators seek a cost effective and easy to operate comminution circuit. The rise of the SAG and ball mill circuit has progressed from an origin in autogenous primary milling, with less common autogenous secondary milling, to the use of higher and higher ball loads in the primary mill in order to maximise capital efficiency.

Along the way, single-stage autogenous milling has been adopted for a few projects where ore competency is reasonably well understood. Single-stage semi-autogenous milling has been adopted in many forms, ranging from the run-of-mine (ROM) mills in South Africa to its use as a capital cost effective circuit for small to medium sized gold projects in Australia.

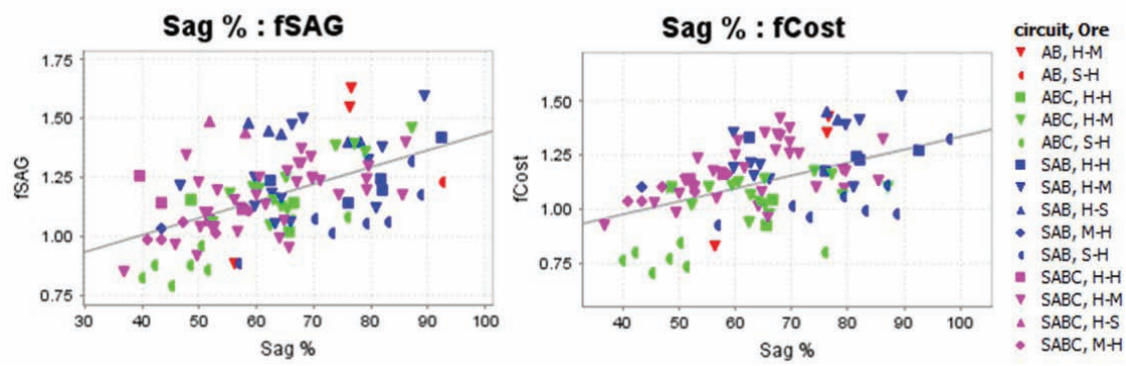

FIG 8 - Energy efficiency parameter and cost efficiency factor as a function of the proportion of total specific energy consumption (kWh/t) drawn by the primary autogenous and semi-autogenous grinding mill (SAG per cent).

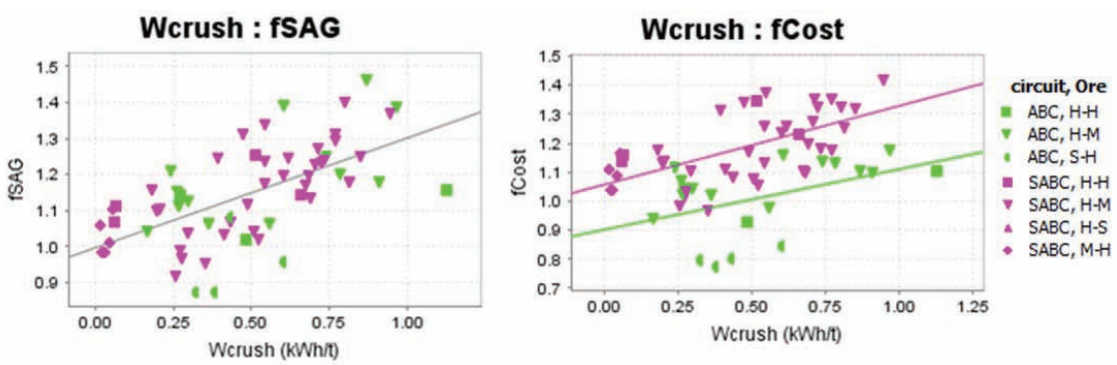

FIG 9 - Energy efficiency parameter and cost efficiency factor as a function of crusher specific energy (kWh/t) consumption in ABC and SABC circuits.

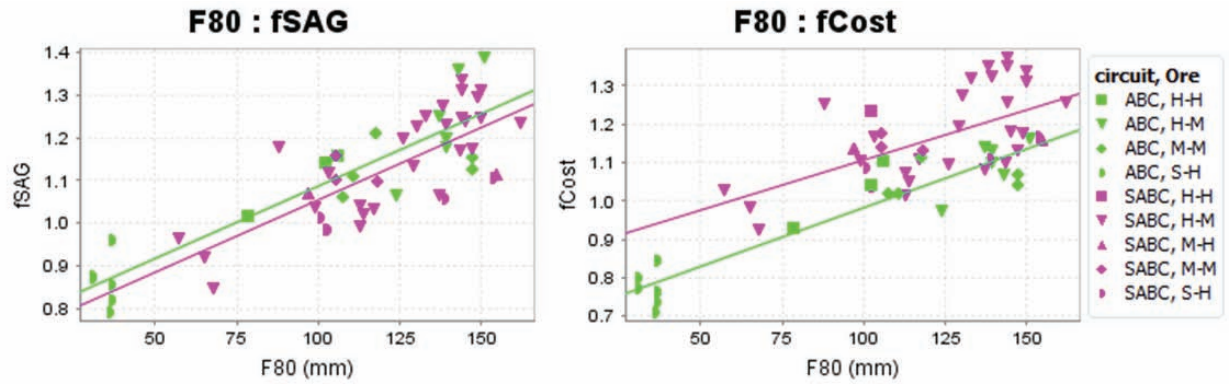

FIG 10 - The effect of feed size on energy and cost efficiency of ABC and SABC circuits.

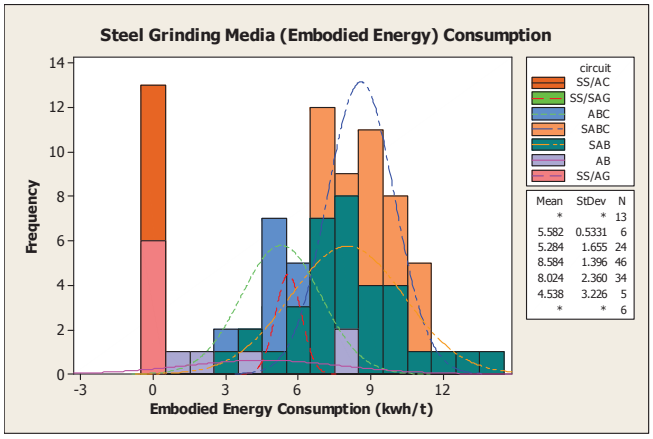

FIG 11 - Indirect (embodied) energy consumption distribution.

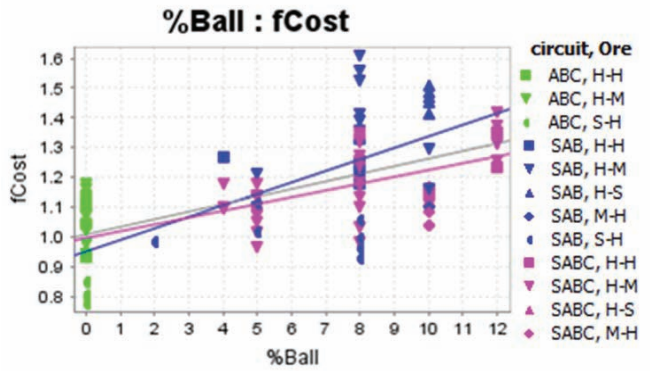

FIG 12 - Cost efficiency factor as a function of ball load in semi-autogenous grinding mills.

To some degree mill operators are stuck with the circuit that the project developers provide. Modifications are limited to addition of pebble crushing to increase throughput and energy efficiency and the addition of balls to an original AG mill to increase throughput (to the limit of the mill shell design tolerance), as well as the reduction of feed size by modifying the blast intensity and/or adding a secondary crushing stage before the AG/SAG mill.

The increasing interest on optimising energy efficiency will remain a matter of cost efficiency in most cases, but there will be a return to the consideration of single-stage and two-stage autogenous circuits as a result of the heightened awareness of eco-efficient operation.

Autogenous milling requires a greater understanding of the variability within the orebody and the way in which ore components impact on mill operation. Current single component mill models will be superseded by multi-component models (Bueno *et al*, 2012).

The benefits for mill operators of autogenous milling include reduced risk during mill maintenance, reduced liner change-outs, no ball handling and reduced noise. The down side is increased variability in performance if controls are not adequate or well understood.

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