EFFICIENCY, ECONOMICS, ENERGY AND EMISSIONS – EMERGING CRITERIA FOR COMMINUTION CIRCUIT DECISION MAKING

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ABSTRACT

The 'smarter' approach to processing described in this paper is limited to the benefits of a more efficient high pressure grinding roll (HPGR) circuit over a traditional semi-autogenous grinding (SAG) comminution circuit. The efficiency challenge described concerns comminution circuit designs that are relatively risk averse and compliment current mainstream engineering practice. The HPGR efficiency assessment aims to motivate more widespread use of HPGR technology, particularly for the copper and gold mining industry.

The summarised results presented stem from the completion of several SAG versus HPGR trade-off studies conducted in the past few years. Trade-off studies primarily relate to evaluating efficiency in engineering studies in terms of energy and project economics. In this paper, an additional sustainable aspect incorporating the impact on environment is evaluated. The concept is presented through the analysis of three case studies where 'typical' mines A, B and C are viewed by considering the impact the design has on the environment. The methodology followed culminates in new measures, standards and targets that can be used by engineers to aid the decision making and process that ultimately justifies plant designs which are eco-efficient and more sustainable.

The results show that a 15 - 20 per cent reduction in direct energy (kWh/t or 'energy cost') is achievable through the use of HPGR circuit designs. HPGR circuits eliminate the need for grinding media and result in a 23 - 25 per cent reduction in operating "dollar" costs. The salient feature from evaluating HPGR circuits over SAG-based circuits in terms of reduced environmental impact (or reduced carbon footprint) showed that up to 26 - 39 per cent less total energy (direct + embodied energy) was required to process the same quantity of ore and produce the same quantity of metal. This appears to be a generic feature of HPGR circuits irrespective of the operating conditions.

Keywords: energy efficiency, HPGR, economics environment

INTRODUCTION

Eco-efficient and sustainable development initiatives are currently linked to the "energy cost" and "dollar cost" savings and not always the "environmental cost", which is normally the traditionalist's objective. In future, direct and indirect energy savings and the impact on the environment should be targeted and analysed in conjunction with real "dollar costs savings". This results in a decision based approach better suited to the environment and sustainability.

The developed and under-developed countries of the world continue to grow. The world now consumes energy in ferocious quantities as this expansion continues, putting renewed pressure on the energy intensive minerals industry to innovate and abate these trends. Mineral processing plant design employing hpgr technology has been an item of great interest at major conferences over the past 6-8 years. Sessions and whole days dedicated to better understanding its application, particularly with respect to energy efficiency, reduced operating costs, overall environmental impact and very recently carbon footprint have been common. Rarely though have all of these aspects been analysed and presented simultaneously. Analysis is often complicated when circuit are designed for different countries under very different social and climatic circumstances.

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The holistic approach presented here in which the workings of economics, energy and the environment are assessed all help towards understanding the important concept of reduced carbon and energy footprints that are linked to the environment, so-called green-house gasses and global warming.

DRIVERS OF CHANGE

This paper assesses the benefits of implementing HPGR grinding technology into comminution circuit design. Three key questions are raised to give an indication as to what is driving the need for this process to be implemented.

1. On a global scale which commodities should be targeted to obtain the greatest impact to lessening environmental degradation and carbon footprint?

A1: Direct energy use in comminution processes was reviewed by Daniel (2007) and showed that 0.56 per cent (87 TWh) of the global net electrical energy consumption of 15,500 TWh per annum is used to crush and grind non-ferrous ores. Of this, 33 per cent and 53 per cent of this energy is required to process gold and copper ores, respectively. The comminution circuit within a minerals processing circuit is the largest energy consuming section (up to70 per cent), and often accounts for a large component of the capital and operating costs associated with mineral production.

2. In production, particularly in comminution circuits, which are responsible for the most energy use, and which are the most energy intensive.

A2: Copper and gold miners/producers are very energy intensive as far as commodities are concerned because only a relatively small amount of metal is produced. Diamonds and rare earth metals associated with the platinum group of minerals are possibly the most energy intensive commodities of all minerals. However, on a global scale, these commodities provide less impact to environmental degradation. This suggests that from an environment and sustainable perspective, HPGRs should be targeted at the gold and copper mining industry. As such the next generation HPGR circuit designs as those proposed by Morley and Daniel (2009) are likely to be the most effective way in reducing comminution energy and associated carbon emissions.

3. What are the benefits of using HPGR technology with respect to energy efficiency, environmental impact and carbon footprint (SAG vs. HPGR)?

A3: The paper sets out to answer this and includes the themes of energy efficiency, economic efficiency in engineering design and environmental efficiency.

EFFICIENCY, ECONOMICS, ENERGY AND THE ENVIRONMENT

Eco-efficient comminution flow sheets are not complex and are based on simple open circuit concepts. The risk associated with the concepts are process related, and also carry an increased engineering costs due to a new design basis. Lane (2008) has demonstrated a path of engineering design that still includes conventional wisdom, and in which compact design concepts can equally improve the environmental and economic impact.

Greater eco-efficiency can be realised by reducing the consumption of mill liners and grinding media. Though the "dollar cost" of comminution is normally accounted for as a direct electricity expense in the process, and is rarely considered for its overall energy cost or "embodied energy" of manufacturing the steel in the liners and grinding media, amounts to up to 4-6 kWh/t. Combining the concepts, "eco-efficient comminution" and "compact design" has a significant impact on project economics.

Copper and gold concentrators vary in size. A common sized concentrator may treat 17,000 t/d (6.2 Mt/a),a larger concentrator 48,000 t/d (16.2 Mt/a). Some of the large concentrators considered today treat 260,000 t/d (95 Mt/a) with multiple processing trains. Two of the largest HPGR concentrators in operation are Boddington and Cerro Verde. These treat 104,000 t/d and 108,000 t/d, respectively. Toromocho in Peru is a good example of a new project which is looking at multiple 40ft x 26 ft SAG mills (28 MW) and the worlds largest ball mills (22 MW) in a conventional circuit designed to treat 120,000 t/d (44 Mt/a)(Mining-technology,2010).

Energy efficiency

Many publications (Anguelov Ghaffari and Alexander, 2008; Rule, Minnaar and Sauermann, 2009; Rosario and Hall, 2008; Marsden, 2008; Patzelt *et al*, 2006; Povey, 2009) focus attention where alternative flow sheets are claimed to have energy benefits of up to 50 per cent. In some instances a holistic approach to analysing the total energy required to produce the metal is presented. The analysis of the interactions between the ore properties, required throughput rate, cost of energy and cost of grinding media are presented. The comparative analysis of assessing HPGR vs. SAG within the industry is not standardised. Circuit designs are evaluated on a case-by-case basis. Energy efficiency is often misquoted and requires a formal definition. Here, energy efficiency is defined as, the difference in energy, expressed as a percentage between the HPGR circuit design and the SAG based circuit design.

Economic efficiency

Where there is marginal differences (<10 per cent) in the capital cost of a SAG vs HPGR flow sheet designs (not studied in this paper), there may well be a larger difference in the "energy footprint" and, hence, lesser environmental impact and associated reduced "carbon footprint".

Environmental efficiency

New eco-efficient comminution circuit options that include a simple analysis of "dollar cost" and "energy cost" are examined. The total energy consumed in a grinding circuit, which includes the "embodied" or indirect energy is used in the comparative analysis.

SAG CIRCUIT DESIGN VERSUS HPGR CIRCUIT DESIGN

HPGR's are compact devices that require a small footprint; they are flexible in that machine settings (pressure, roll speed) may be adjusted to react to ore variations whilst maintaining a high throughput. The flow sheets used in the comparative study are a conventional SAG based design (Figure 1) versus a conventional HPGR circuit design (Figure 2).

COMMINUTION AND ORE COMPETENCY

Mineral resources are heterogeneous and consequently have variable physical, chemical and mineralogical properties. Invariably, ore processed in the first few years is different to ore processed in the latter years, typically in physical (competency and hardness) and mineralogical (liberation) characteristics. Over time, circuits often struggle to maintain throughput and some unit processes become a bottleneck. Often this is the SAG mill and the circuit is termed as a SAG limiting circuit.

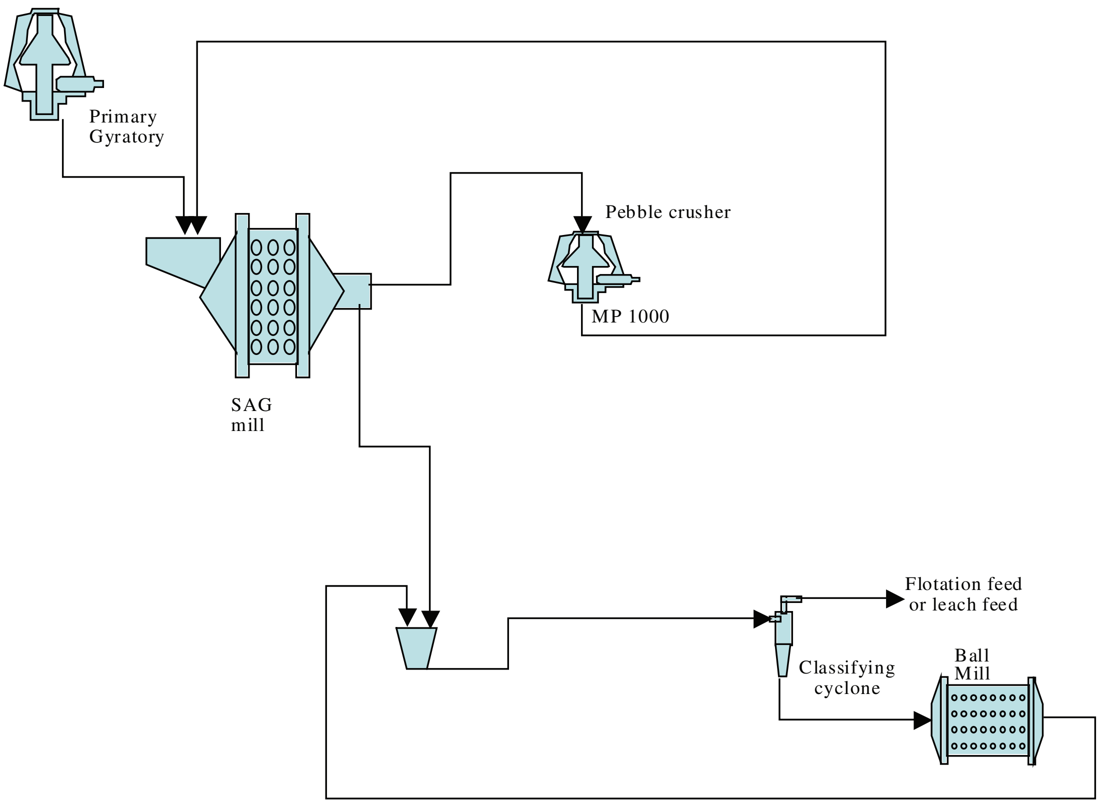

FIG 1 - Conventional SAG Circuit (SABC) – single train.

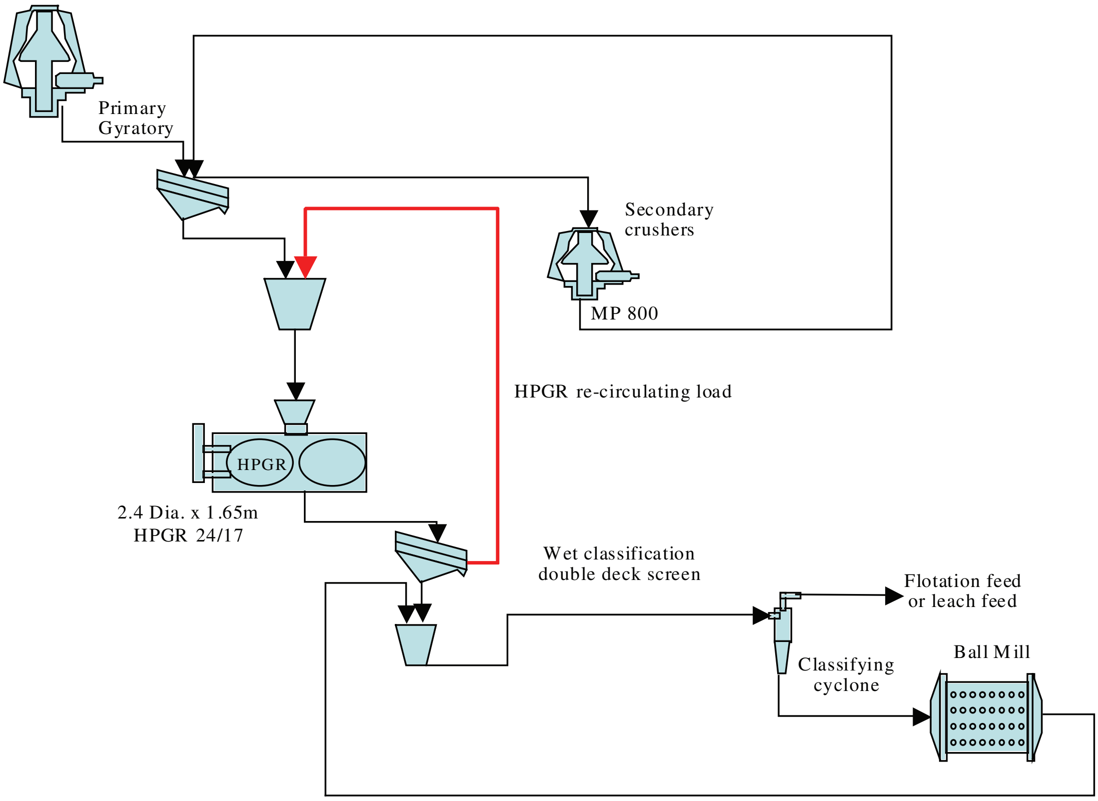

FIG 2 - Conventional HPGR circuit design – single train.

The SAG mill becomes limiting when the coarse ore becomes more competent. Ore competency or resistance to impact breakage within the SAG mill can be measured using one of several tests, namely SPI®, JKDWT Axb and the SAG mill comminution test (SMC® test). Although any of the above-mentioned tests can provide data to support the analysis in this paper, this evaluation uses the JKDWT Axb values.

SMC® or SPI® are cost-effective tests that are used to characterise ore types within an ore body in green-field or brown-field operations. A number of tests can be completed quickly to get information about the resource. Data from these tests characterise different ore types that will be presented to the comminution circuit are used to determine how the circuit will respond in terms of throughput and grind size.

As a general rule, ore competency and hardness increase with depth within the pit. Over time, the throughput of mills initially sized for the operation can decrease as the SAG or ball mill becomes limiting. Maintaining throughput can be alleviated to a degree by either increasing ball charge and mill speed with initial design specifications, or with subsequent circuit modifications such as pebble crushing and secondary crushing feed to the SAG mill. Once the initial design limits are exceeded, both reduced throughput and a coarser grind size are operating risks.

HPGR's are compact devices that require a small footprint; they are flexible in that machine settings (pressure, roll speed) may be adjusted to react to ore variations whilst maintaining a high throughput.

For the purpose of comparative assessment between SABC and HPGR circuits, three "typical" mines (A, B and C) each with characteristic ore types have been selected. JK DWT Axb values, average ore densities and Bond ball mill work indices for each of the mine cases are shown in (Table 1).

The base case throughput is 1625 t/h or 13.0 Mt/y for each mine. SAG mill sizing calculations for each of the ore conditions for the nominated throughput were determined through an empirical SAG throughput model (Table 2).

The SAG mill in SABC baseline circuits A, B and C are compared with other SAG mills in similar circuits operating within the industry in Figure 3 (Veillette and Parker, 2005). The cases selected provide a good coverage of industry experiences – excluding the extreme competency and the very "soft", highly friable conditions.

TABLE 1

Ore properties for mines A, B and C.

Ore property	Units	Mine A SABC	Mine A HPGR	Mine B SABC	Mine B HPGR	Mine C SABC	Mine C HPGR
Ore Property							
A*b		36	36	44	44	61	61
s.g.	t/m^3	2.63	2.63	2.66	2.66	2.85	2.85
BWI	kWh/t	16.0	16.0	14.0	14.0	10.0	10.0

TABLE 2

Performance characteristics of SAG mills operating at mine A, B and C.

Parameter	Units	Mine A	Mine B	Mine C
Feed rate	t/h	1625	1625	1625
Primary crush CSS	mm	150	150	150
Predicted SAG F80	mm	120	105	88
Ore property (JK DWT)	Axb	36	44	61
Ore density	g/cm^3	2.63	2.66	2.85
Mill diameter (shell)	ft	40	38	36
Mill length (EGL)	ft	20	18	15
Mill speed (critical)	%	76	76	76
Ball charge	%	12	12	12
SAG mill gross power	MW	16.2	13.0	9.6
SAG mill specific energy	**kWh/t**	**10.0**	**8.0**	**5.9**

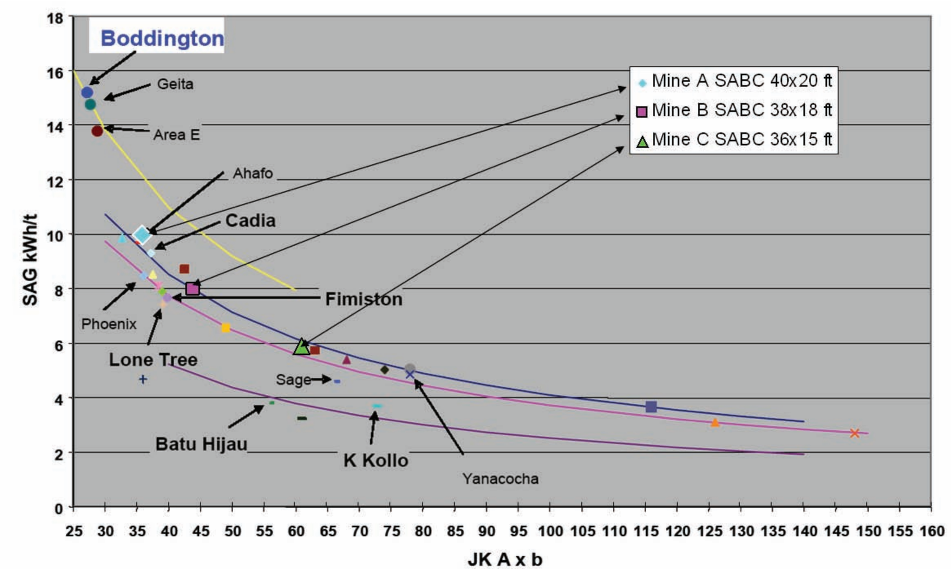

FIG 3 - SAG specific energy of mines A, B and C relative to the published Newmont Mining plant database (Veillette and Parker, 2005).

EFFICIENCY COMPARISONS FOR SABC AND HPGR CASES

The comparative analysis for SABC and HPGR cases assesses energy efficiency, operating cost and environmental impacts.

Direct energy

The total specific energy is a measure of the direct energy required. The total installed power for the comminution equipment can then be calculated. These are shown for SABC and HPGR circuits for Mines A, B and C in Table 3 as well as the relative unit power and total installed power comparisons.

TABLE 3
Energy efficiency of SABC and HPGR circuits.

Parameter	Units	Mine A SABC	Mine A HPGR	Mine B SABC	Mine B HPGR	Mine C SABC	Mine C HPGR
$F80$	mm	121	121	106	106	88	88
$F80_{HPGR}$	mm		45		37		40
$T80_{HPGR}$	mm		6.0		4.5		5.0
$T80_{SAG}$	mm	0.9		1.2		1.5	
P80	µm	106	106	150	150	150	150
SAG vs HPGR							
Secondary crushing	kWh/t		0.4		0.4		0.2
HPGR	kWh/t		3.0		2.6		1.9
Ball mill	kWh/t		13.5		9.3		6.8
Pebble crushing	kWh/t	0.2		0.2		0.2	
SAG (Ecs)	kWh/t	10.0		8.0		5.9	
Ball mill (Ecs)	kWh/t	9.7		6.6		5.0	
Total circuit specific (direct) energy	**kWh/t**	**19.9**	**16.9**	**14.8**	**12.3**	**11.1**	**8.9**
HPGR circuit specific energy reduction	kWh/t		3.0		2.5		2.2
Total circuit pinion power	MW	32.3	27.5	24.1	20.0	18.0	14.4
Installed power saved	MW		4.8		4.1		3.6
Direct energy saved	%		**15.0**		**16.9**		**19.8**

The direct energy saving with a HPGR circuit is relatively constant and expected to be 15-20 per cent for the range of conditions specified. The installed energy saved for comminution also reduces power supply to the site. The energy saving is greater when the ore is more competent.

Operating cost

The operating cost is a measure of economic efficiency. A comparison of operating costs between SABC and HPGR circuits is shown in Table 5. Key assumptions are as follows:

- power is from grid supply and costs $0.070/kWh;
- grinding media consumption rate is 0.4 kg/tonne for the SAG mill;
- grinding media consumption rate is 0.5 kg/tonne for ball mills in the SABC circuit;
- grinding media consumption rate is 0.55 kg/tonne for ball mills in the HPGR circuit;
- grinding media costs $1200 per tonne, delivered to site.

Ball mill media consumption in the HPGR circuit is higher due to coarser transfer sizes. Grinding media consumption rates for SAG mills and ball mills are and based on conventional practices and well documented methodology.

The main benefits in the HPGR circuit over the SABC circuit are the significant reduction in grinding media, nearly all from the SAG mill, and the lower power cost, due to the lower specific energy with this circuit.

The reduction in unit operating cost with a HPGR circuit is significant at $0.54 to $0.66/t over the range of conditions. which is comparable to Cerro Verde at 0.37 US$/t (Vanderbeek, 2006). Site specific variations will occur with where unit energy cost, media consumption rates and grinding media costs are significantly different. Nevertheless, this assessment shows that a reduction in operating costs of about 25 per cent can be realised with HPGR circuits.

Embodied energy

The embodied energy, or "emergy", is defined as the quantity of energy necessary for the fabrication of a specific material or consumable used in the process. When measuring embodied energy, all energy inputs from raw material extraction, transport, manufacturing, assembly, installation and others are

TABLE 4

Operating cost comparison between SABC and HPGR circuits.

Parameter	Units	Mine A SABC	Mine A HPGR	Mine B SABC	Mine B HPGR	Mine C SABC	Mine C HPGR
Throughput rate	t/h	1625	1625	1625	1625	1625	1625
Power cost	c/kWh	7	7	7	7	7	7
Grinding media cost	$/t	1200	1200	1200	1200	1200	1200
SAG mill liner replacement per year	$ M	5.0		4.6		4.0	
HPGR rolls replacement per year	$ M		4.6		4.6		4.6
Grinding media consumption SAG mill	kg/t	0.40		0.40		0.40	
Grinding media consumption ball mill	kg/t	0.50	0.55	0.50	0.55	0.50	0.55
Total media consumption	**kg/t**	**0.90**	**0.55**	**0.90**	**0.55**	**0.90**	**0.55**
SAG mill liner cost	$/t	0.39		0.35		0.31	
HPGR roll cost	$/t		0.36		0.35		0.35
Power	$/t	1.39	1.18	1.03	0.87	0.78	0.62
Grinding media	$/t	1.08	0.66	1.08	0.66	1.08	0.66
Operating cost total	**$/t**	**2.86**	**2.20**	**2.46**	**1.88**	**2.17**	**1.63**
Operating cost saving	$/t		0.66		0.58		0.54
Power saving, annual	$ M		2.7		2.1		2.1
Media saving, annual	$ M		5.4		5.4		5.4
Cost saving annual	$ M		8.1		7.5		7.5
Cost saving	**%**		**23.1**		**23.6**		**24.9**

TABLE 5

Circuit efficiency expressed in terms of carbon footprint.

Total energy balance or "energy cost"	Units	Mine A SABC	Mine A HPGR	Mine B SABC	Mine B HPGR	Mine C SABC	Mine C HPGR
Grinding media consumption	t/y	11,700		11,700		11,700	
Grinding media consumption	t/y		7,100		7,100		7,100
Embodied energy in grinding media	kWh/t	6,000	6,000	6,000	6,000	6,000	6,000
Embodied energy consumed	GWh/y	70.2	42.6	70.0	42,8	70.0	42,8
Embodied energy saved	GWh/y		27,6		27,2		27,2
Embodied energy component	kWh/t	5.4	3.3	5.4	3.3	5.4	3.3
Embodied (indirect) energy saved	kWh/t		2.1		2.1		2.1
Direct energy saved	kWh/t		3.0		2.5		2.2
Reduced total energy	**kWh/t**		**5.1**		**4.6**		**4.3**
Reduced energy as "carbon footprint"	**%**		**25.6**		**31.1**		**38.7**

considered. Embodied energy as a concept seeks to measure the accrued energy cost of an item. From an increasing regulatory regime and awareness of social pressure relating to greenhouse emissions have emerged sustainable development initiatives as well as improvements in comminution energy efficiency.

In the HPGR case, replacement of media and liners used in grinding mills represents a saving in emergy. As a direct cost, it represents a saving in operating costs for materials consumed in the process. As an indirect cost, it accounts for (has already expended) approximately 6 kWh/kg of steel grinding media. In the SABC grinding circuit the grinding media consumption rate of 0.9 kg of steel per tonne of ore treated is equivalent to an additional 5.4 kWh/t of indirect energy. The indirect energy saved in a HPGR circuit by not using grinding media (0.90 – 0.55 kg/t) is equivalent to 2.1 kWh/t. The total energy accountability which recognises direct and indirect energy effects, and expresses these as a percentage of an emissions criteria, such as "carbon footprint", are presented in Table 5.

On the basis of total energy accountability and environmental impact, HPGR circuits are 26-39 per cent more efficient for this range of conditions.

Eco-efficient and sustainable development initiatives are not only linked to direct dollar cost savings, but also the indirect energy cost savings. This analysis demonstrates this can be achieved through a significant reduction in the consumption of comminution circuit grinding media.

CONCLUSION

HPGR is an effective comminution device for brown-field retrofits to increase plant capacity or maintain plant capacity or to maintain plant capacity when deeper underground ores become more competent.

The comparative case study in this paper examine the energy and cost efficiencies for a SABC and HPGR based comminution circuits.

The ore conditions nominated for this case study lie within the range experienced in industry. This work shows:

1. HPGR is more (direct) energy efficient and reduces overall grinding energy between 15-20 per cent. This may vary for specific applications, depending on the target grind size and ore characteristics.
2. HPGR is more cost efficient and reduces comminution costs by 23-25 per cent. This may vary for specific sites, depending on the unit cost of energy, unit cost of grinding media and the rate of grinding media wear.
3. HPGR reduces total (direct and indirect) energy by 4.3-5.1 kWh/t.
4. The total energy accounted for by a HPGR circuit reduces the environmental impact or emissions criteria (such as carbon footprint) by 26-39 per cent.

Direct energy, economic and operating cost efficiencies are traditional criteria employed in the selection of comminution circuits. In addition to these, embodied energy, environmental impact and emissions criteria are playing an increasing role in decision making for comminution circuits.

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