INTEGRATING THE STRENGTHS OF SAG AND HPGR IN FLEXIBLE CIRCUIT DESIGNS

*M.S. Powell[1,4], H. Benzer[2], A.N. Mainza[3]

[1]*University of Queensland, JKMRC - SMI*
40 Isles Rd
Indooroopilly, Australia, 4068
[4]*Co-operative Research Centre for Optimising Resource Extraction (CRC ORE)*
*(*Corresponding author:* malcolm.powell@uq.edu.au*)*

[2]*Hacettepe University*
Dept. of Mining Engineering, Mineral Processing Division
Beytepe-Ankara
Turkey, 06800

[3]*Centre for Minerals research*
University of Cape Town
Rondebosch, 7700
South Africa

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ABSTRACT

Despite the claims of energy efficiency and the considerable development that has gone into dramatically extending rolls' life and facilitating rolls' change-out, in the six years since the last SAG conference, only a few HPGR operations have entered the realm of mineral processing. Risk barriers to the take-up of new equipment or processes are: a massive increase in materials handling issues as well as in the number of pieces of equipment required, low total circuit potential energy savings, and similar or higher capital costs. An alternative route is to make use of the complementary strengths of the HPGR and SAG in hybrid circuits. Minimising materials handling issues, providing an ideal balanced feed to the AG or SAG mill, and improving controllability through shifting grinding load as the RoM feed changes, are all potential major advantages to this approach. Conceptual circuit layouts, based on real measured ore and equipment data, are presented here to illustrate the potential production upside, the reduction in operating costs and the reduction in the physical and energy footprints.

KEYWORDS

HPGR, SAG mills, circuit design, energy efficiency, flexible operation

INTRODUCTION

The HPGR has been touted as the energy efficient replacement of the SAG mill and as such has received considerable attention in the literature and at conferences. However, the reality is, that in the six years since the last SAG conference, only a few full-scale HPGR operations have entered into the mineral processing field. Aside from the standard risk barriers to the take-up of new equipment or processes, it has been noted that the HPGR has not delivered a convincing case in designs that have considered both SAG mill and HPGR grinding as contenders for the processing routes. The massive increase in materials handling issues (Powell et al., 2011a) and an increase in the number of pieces of equipment required, are major drawbacks of these HPGR circuit layouts. An additional barrier is that existing SAG circuits will not be scrapped to make way for a new process.

It is proposed that there is considerable potential to make use of the complementary strengths of both comminution devices by adding the HPGR to current circuit expansions, and possibly incorporating a SAG/HPGR duo into new circuit design. When compared with traditional crushing circuits, clever circuit design, supplemented by some key equipment enhancements, should allow minimal materials handling issues,, while providing an ideal balanced feed to the AG or SAG mill to maximise the fine grinding capability of this equipment. As RoM feed type changes, the grinding load can be shifted between the different devices to maintain a stable throughput and target product size, with a minimal installed surplus capacity in the circuit.

Conceptual circuit layouts, based on realistic ore and equipment data, are presented. Key engineering issues to be addressed in order to maximise the benefit of such an integrated circuit design; the potential production upside; the reduction in operating costs and the reduction in the energy footprint of the sites are discussed.

BACKGROUND MOTIVATION

The concept of mine-to-mill was introduced in the 1990's to improve the performance and throughput of SAG mills by up to 20%, through integration with the mining process, specifically blast design (Mine to mill conference, 1998; Morrell & Valery, 2001; Lam, Jankovic, Valery & Kanchibotla, 2001). The concept hinges off playing to the strengths of the SAG mill, utilising large rocks to grind small ones, while minimising the slow grinding mid-size 'critical-size' material in the feed. It also increases the underutilised ability of blasting to produce a significant fraction of very fine material, minus 500 µm, that reduces the fine grinding load in the milling circuit.

Despite the ongoing success of this approach, there are new drivers that require a considerable step change beyond this rationale to meet the new challenges facing our industry.

- Energy – The mining industry is being targeted as an excessive user of energy. Real cost increases in production, carbon taxes and societal pressure are all driving a demand to decrease energy usage.
- Water – Historically this has been a tiny part of the mining cost, so has had a low priority. However, the mining industry is not being allowed to out-compete agriculture and society at large for this precious resource. The cost now is not so much in dollars but in limitation in production due to a shortage of availability - current or potential.
- Massive low grade ore bodies – Inevitably ore grade is dropping as we use up our best resources. This leads to vastly increased tonnages and treatment of waste; larger and deeper pits; and often these ores are more competent than older ore bodies. All of these factors massively drive up the energy consumption per tonne of metal produced.
- Increasing demand for natural resources – this drives up the total amount of mining taking place and hence the total energy and water usage within the mining sector.

As presented in the work of Powell and Bye (2009), the consequence of the increase in demand and the drop-off in grade is that saving 10 – 20% of energy usage in terms of kWh/t of ore, still results in a massive increase in total energy usage per unit of product. Based on the trends of mineral usage published in the report on Australian minerals usage, ABARE (2007), the average rise in consumption is about 3% per annum. It is estimated that ore competence, in terms of kWh/t to treat, is increasing at about 1% per annum and ore grade dropping at about 1% per annum. Based on these figures, to achieve the oft-stated company targets of 10-20% saving in absolute energy (RioTinto, 2008; BHPB, 2009; Anglo, 2009), specific energy usage (kWh/t of ore treated) needs to drop below 40% of the usage in 2000 by 2020 and to below 20% by 2050!

Applying current technology will not achieve anything near this objective. Clearly a whole new approach is required. This will undoubtedly be multi-pronged; from application of current technology through to innovative solutions based on blue-sky research. The current paper will not attempt to address this entire issue, but will stray into a wider area than just the application of technology to achieve a certain circuit throughput at a given grind at the lowest *current* operating costs. We have emphasised *current*, for if the mining houses do not allow for the inevitable massive increases in the cost of energy their operations will be caught sadly short in the future.

Comparison of energy consumption

Comparison of different processing routes is severely hampered by the oft-used P80 marker. How can such a simplified analysis cope with multiple P80's across different product streams in a multi-stream circuit? Using P80's does not allow for the impact of grind size varying as a function of economic recovery in different sub-processes.

What is really needed is a measure of the energy used to achieve the recovery size. The simple size-specific energy figure of kWh/t final product is a good indicator of this. The indicator size is chosen according to the desired product size, say 120µm for a coarse grained mineral, but 30µm for a fine grained mineral. The work of Musa & Morrison (2009) addresses the potential comparative techniques in some detail.

A major factor that is generally overlooked in assessing a grinding circuit cost, is the very high embodied energy in the production of steel consumables. The work of Pokrajcic and Morrison (2008) has shown that the ball consumption in a standard grinding circuit contributes 50% to 100% more energy overhead to the direct energy consumption. Thus, designing the comminution circuit to reduce or eliminate ball consumption has a major impact on the overall environmental impact of the circuit.

Energy saving potential

According to the calculations of Musa & Morrison (2009), the practical energy efficiency of milling is in the range of 30% to 40% for Ball to SAG milling, where efficiency is defined as the fraction of input energy that is utilised in the breakage process. This implies that the amount of input energy going into the grinding process can possibly be halved, to give an efficiency range of 60% to 80%. This gain would be through massively improved equipment utilisation. This will not be achieved through equipment tweaking.

Compressed bed breakage has been reported to provide up to 20% energy saving over milling, and many design studies of the application of HPGR's were presented at the SAG (2006) conference. The HPGR holds promise for reduction of energy use, and for integration into dry or low water use circuits. However, it is the opinion of the authors, that extensive development is still required to determine how best to engineer them into our existing circuit technology. When not properly designed into the circuit they can bring a host of new issues to the fore, such as screening problems, a multiplicity of conveyors and dust generation (Powell et al., 2011a).

In order to achieve the energy saving objectives and corresponding decrease in operating costs, a number of approaches have to be integrated and the process as a whole has to be optimised, not simply tweaked on a unit by unit basis. It is proposed that careful integration of HPGR and SAG mills is one such approach and this is tackled in the current work.

EQUIPMENT STRENGTHS AND WEAKNESSES

The HPGR, SAG and AG mills all have different strengths and weaknesses. Therefore, it is appropriate to first consider these before proposing how to integrate them.

HPGR

Mills in which particles are broken by compression are used extensively in the cement and coal industries. Their main advantage is that they use less energy for most comminution requirements. Their use in the mineral industry is mainly with some diamond and iron ores, although they have been used with copper, platinum and gold ores.

Strengths

- Deal well with hard rock
- Low sensitivity of throughput to variations in rock hardness and feed size
- Can wind throughput linearly up and down with rolls' speed
- Proven long rolls' liner life (8000-16000 hrs)
- Rapid change-out of rolls (14 hours)
- Large degree of reduction (4 to 50) with a substantial fraction of fines. In closed circuit can easily obtain 40% of sub 1 mm product

- Good energy efficiency (Aydogan and Benzer; 2011)
- Introduction of micro-cracking results in improved grindability with less power consumption (Dunne, 2004)
- May provide increase in metallurgical performance of the downstream process.
- Easy control due to the short residence time, allowing a quick response to operational parameter changes.

Weaknesses

- The possible need to deagglomerate the compressed cake in the product prior to screening
- Dry processes that produce a high percentage of fines have an inevitable dust issue
- Vulnerability of the rolls' surface to steel and large highly competent pebbles
- Product particles can be up to the floating gap width in size, so external screening is generally essential
- Strict feed top size control is crucial
- The pressure profile along the roll length results in a higher wear rate in the mid section of the rolls
- Sensitivity to higher moisture content means that feed moisture should generally be kept below 7%
- Cushioning effect of the soft component on the hard component can result in a build-up of a hard component in the recirculating load.

SAG mill

The SAG mill should be well known to this audience, but a few points salient to the current discussion are listed.

Strengths

- Economies of scale of a single unit for high throughput low-grade circuits, providing the lowest cost per tonne of ore treated, based on both capital and operational costs.
- Massive throughputs of 2 500 to 4 000 tph in the largest mills
- When having variable speed (generally only supplied for the large units using wrap-around motors) they can provide rapid response to changes in feed
- Ability to manipulate the rock-to-ball ratio to optimise operation and to deal with long-term changes in feed type
- Ability to increase the throughput by up to 40% through the installation of pebble ports, recycle crushers and extra downstream milling capacity
- Low control and operator overhead for the limited number of pieces of equipment in the circuit
- Relatively robust operation with fluctuating feed types.

Weaknesses

- Throughput and product size vary with feed size and competence
- They tend to remain a control challenge in many operations, with filling and power draw drifting and cycling continuously
- All, or a substantial fraction, of the processing plant goes down with the SAG mill, as they are often single stream or at most three in a circuit.
- Many of the large mills that are pushed to high throughput by pebble porting and low slurry densities are limited by absolute discharge limitations, resulting in slurry pooling and loss of power

- High cost of grinding media despite using rock as part of the media: figures can run as high as $7 million per month
- Despite using steel grinding media, the load still rapidly builds up with an increase in competent or large feed, with a resulting substantial loss of feedrate, in the order of 20% reduction, is regularly noted with ore-bodes that have high competence zones.

AG mill

The Autogenous mill has received less favourable coverage than the SAG mill, but does carry a number of marked advantages.

Strengths

- Zero media consumption
- Lowest operating costs
- Ability to supply pebbles media to the second stage of grinding, such as at Aitik Boliden and LKAB mines in Sweden (Powell et al., 2011b)
- As they produce a finer grind, less secondary grinding capacity is required compared to a SAG mill circuit.

Weaknesses

- For an equivalent throughput to a SAG mill, a considerably larger mill is required. A 40 ft SAG mill with 15% balls will draw 20 MW, an equivalent AG mill will need to have a diameter of 44 ft (at a higher filling and the same aspect ratio) or it must be a lot longer.
- Sensitivity to the supply of competent rock – both by size and competence – in the RoM feed. This is both a short-term control issue and a long-term mine planning challenge, so far as understanding the geometallurgy and controlling the blend or balance of rock types to the mill over life of mine.
- Lower ability to vary throughput – large rock has to be retained in the mill as media so the size of pebble ports is limited
- Trickier to control as the feed varies

OPPORTUNITIES

Before focussing in on the unit processes, it is, as emphasised this paper, necessary to consider them as part of an integrated mining and mineral extraction process. A brief overview of the associated opportunities and issues is presented here, to provide context to the proposed circuits, since these proposed approaches are not about localised improvement measured in terms of dollars per tonne to grind to a *given* (i.e. assumed to be irrefutable) P80 product size.

Mining

This is the first stage of comminution and a huge driver of the downstream milling performance. As proposed by Powell & Bye (2009), this needs to be considered in a far richer context than the mine-to-mill approach, that in essence is only about tuning the blast for one specific piece of equipment - the SAG mill. The mining and blasting technique should be an integral part of circuit design, with a feed-back loop linked to potential circuit design options.

The mining technique also presents significant opportunity for waste removal and progressive upgrade early in the extraction process, such as the removal of coarse sub-grade material prior to any further processing.

Staged reduction

This potentially enables access to the product at various stages along the comminution route, providing these opportunities are designed into the circuit in both mineral processing and physical engineering layout perspectives. Known opportunities are screening after preferential liberation; dense media separation; Grind – recover – grind concentrate – recover (common in porphyry copper).

Progressive upgrade

Rather than aiming to grind the ore to a target liberation size and then hit it with a single massive recovery stage, catering for the average feed grade, this process integrates waste removal and splitting the ore into different grade streams. These streams are then differentially treated to both minimise the amount of work (and hence energy usage) and to target the recovery process best suited to these different streams. The separated streams can be ground to different degrees of fineness according to the value of each stream; such as the low grade stream having a considerably coarser grind, and presenting an opportunity to dramatically reduce the energy usage.

More efficient equipment

A key opportunity is matching the equipment to the duty. A good example is in finer grinding down to P80's of below 40 µm. Although standard ball mills can be used in this application, it is well beyond their range of optimal efficiency, principally due to the balls being far too coarse for the application. In this instance stirred media mills provide dramatic decreases in energy consumption.

Operating equipment close to its optimal conditions is another area where efficiency can be improved. The fact that simple matters such as optimal slurry density (viscosity) in mills and cyclones are so often overlooked or abused in operations, is a rather damning indictment on the efficiency of the industry overall. This may seem a somewhat controversial statement, but in reality, many successful consultants around the world can attest to the success they have achieved at improving operations, through straightforward metallurgical control recommendations. (Sadly these recommendations are often not maintained for long due to staff turnover and competence/training issues.)

Total cost that incorporates sustainability measures

Current NPV costing models do not deal with the wider issues of sustainability, as there is no way of incorporating them. However, it is now being commonly acknowledged by the heads of our industry that mining has to earn its licence to operate. Poor performance or negative impacts at the regional or national level can increasingly limit the access of that company, or the industry as a whole, to further resources in that and other regions. The Centre for Sustainable Resource Processing spun out a new approach, SUSOP – for the assessment of sustainable operations (SUSOP, 2011) to assist in taking on a whole impact and sustainability approach to the development of operations. The CRC ORE is exploring new measures of valuing operations that can incorporate risk, variable recoveries, assessment of new or alternative technologies, variable feed types over life of mine, waste remediation, water costs, etc., into life of mine valuations.

Stabilising circuit response

In simple terms, a variable ore passing through a fixed process must lead to variable recovery. It is well established in all chemical processing that this variability will always lead to reduced recovery. In mineral processing this is considered acceptable: it results in a revenue reduction and is allowed for in the capital cost at the design stage. It is proposed that through higher quality testing and modelling linked to more appropriate valuation techniques, a proper case can be made for building circuits that are intrinsically controllable, and have process control and optimisation built into the design from the foundations upwards.

Integrated approach

It is proposed that mine planning, blasting design, mining method (e.g. block caving), comminution circuit design, concentration process, process control and waste treatment need to be integrated at the design stage to capture considerable benefits in process improvement. Process design should allow for multi-stream and multi-grade circuits. With cost-cutting such a strong driving force in circuit design, strong motivating factors are required to trigger such an approach. Higher energy costs, carbon taxes, and social drivers are one such group of drivers. But another, possibly more persuasive driver, is that, in principle, these circuits can offer both higher recoveries as well as lower energy usage than the single processing route options.

CIRCUIT EXAMPLE

With the inevitable expansion of circuits (in response to higher prices driven by demand increases, over recent years), unit operating costs decrease and this has allowed cut-off grades to fall and ore reserves to be considerably expanded at many operations. Many SAG milling circuits now have at least two parallel circuits, and some have more than four. One then has to ask the question: Is this simple design duplication leading to increased profits? For now, the circuit has the disadvantages of multiple streams while rigidly maintaining an inflexible circuit design - see the "Weaknesses of SAG mills" section. A single stream may be elegant, but four identical ones simply limit the process to the same constrains and pitfalls.

It is proposed that expansions offer the ideal opportunity to introduce flexibility into large circuits. Instead of taking the standard SABC (SAG – Ball mill – recycle crusher) circuit and doubling it up, as in Figure 1, screening and HPGR sections are added (circled in fine dotted lines) as illustrated in the conceptual layout of Figure 2. The circuit ends up with no more equipment than a standard doubling-up expansion.

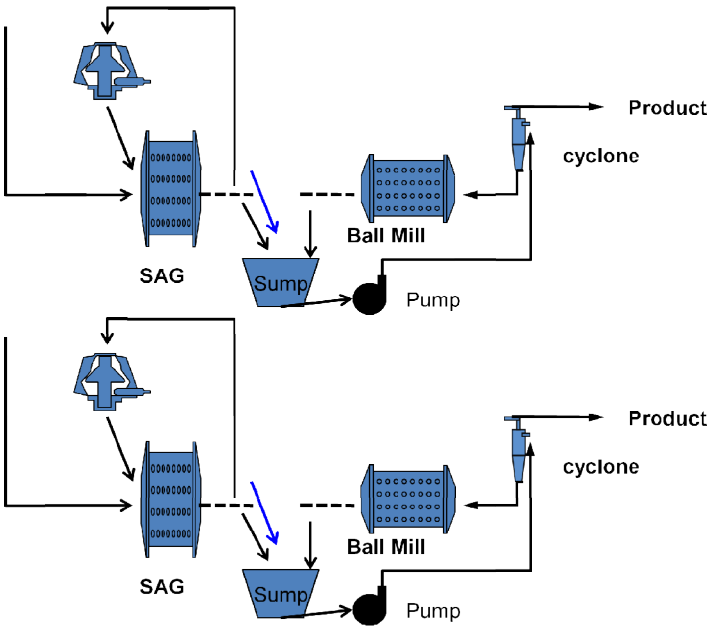

Figure 1 – Standard SABC circuit, doubled for expansion

Hybrid circuit description

The proposed circuit in Figure 2 may appear complex, or at least different, compared to standard SAG circuits, so it demands careful description. This is laid out on the basis of an original circuit treating 1000 tph, with this doubling to 2000 tph.

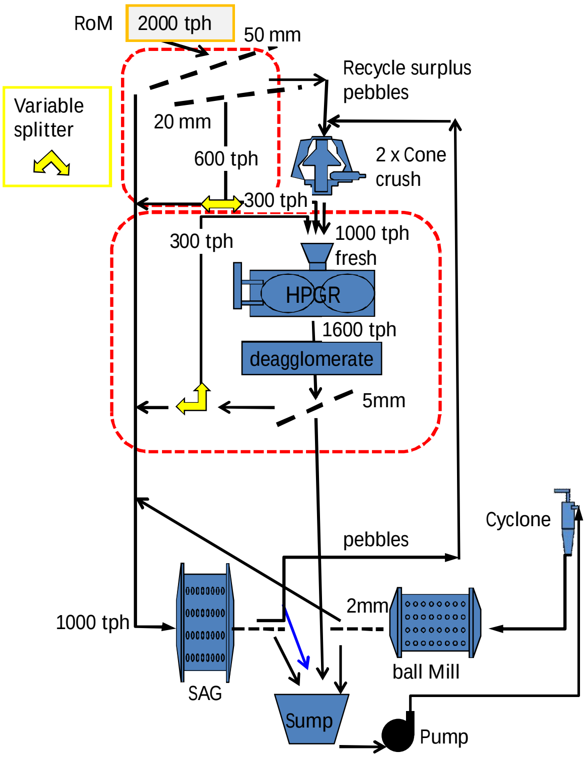

Figure 2 – Base hybrid HPGR-SAG circuit

The three splitter arrows indicate the major new flexible control points in the circuit. These can be used for active process control.

The screening section has a double deck standard square aperture screen with 50 and 20 mm decks. Its purpose is the selection of separate feed sizes for the crusher and the HPGR and the provision of a variable split of the flow in the mid-size to the SAG mill or HPGR. This variable splitter becomes a key control point to deal with variations of ore type and coarseness, with the very different grinding capabilities of the two processes providing flexibility to cope with feed fluctuations. It also allows for future waste sorting. Thus the screening section has a variety of uses and maximum value is gained from this expensive structure.

With the SAG mill receiving the plus 50mm material, standard cone crushers can be used in a secondary application, with a top feed size of 50mm, i.e. F80 of under 35mm – rendering them almost a tertiary crusher duty. The product can be expected to all pass 20 mm; removing the need for screening prior to feeding the HPGR. Removing screening greatly simplifies the circuit: reducing the capital investment, footprint, maintenance and operating costs.

The energy efficient HPGR is used to grind the mid-size fraction that SAG mills grind poorly. A deagglomerator /screening unit housed in a dust controlled environment within a few meters of the HPGR is used to recycle coarse plus 5mm material to the HPGR. The screen undersize reports directly into a ball mill sump, as all the product is guaranteed to be below 5mm. This eliminates dust and classification issues. It is also feasible to use a wet 5mm screen, with the undersize reporting to the ball mill and the damp oversize being recycled. Providing the fresh feed is reasonably dry, the net HPGR feed will still be well within moisture operating limits. The HPGR utilises variable speed to vary the throughput as the feedrate fluctuates with RoM ore variations.

The only recycle conveyors are for the HPGR and the SAG pebble discharge. A storage bin between the crusher and HPGR is essential.

The SAG mill is fed an ideal bi-modal feed from the screening plant. The mill is pebble ported and the pebbles can be used to enable the ball mill to be converted to a pebble mill, see next option. The plant then eliminates the vast majority of the embodied energy inherent in the steel consumption.

Advantages

Expandability – see below
Screening is low in energy and operating cost
No media costs in the HPGR, so the media costs are, at worse, the same as for half the throughput.

Energy-efficient option

An alternative route to retaining the SAG and ball mills is to shift to a fully autogenous operation, with a conversion to AG and pebble mills, as illustrated in Figure 3.

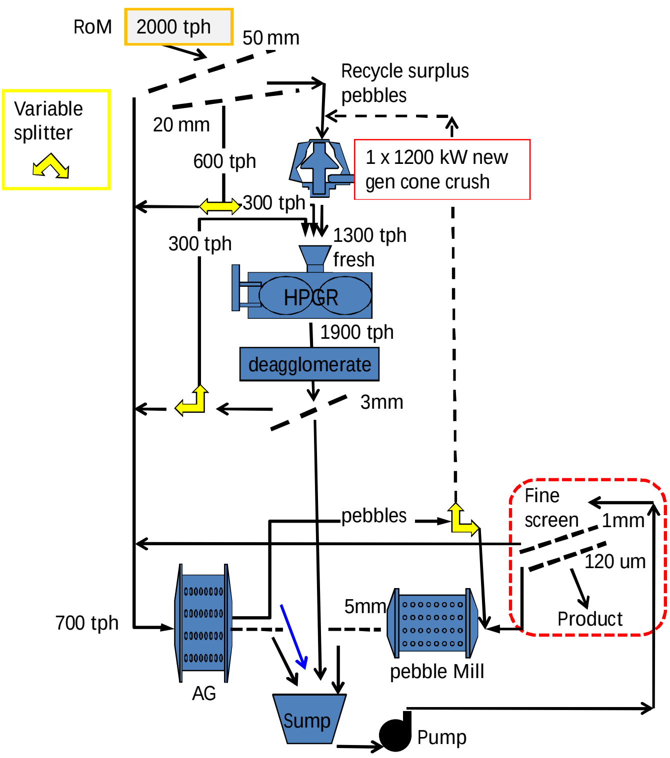

Figure 3 – Energy-efficient expansion option

Sufficient power is installed in the HPGR circuit to reduce the duty on the SAG mill. Initially the circuit may continue to be operated in SAG mode until the HPGR achieves a suitably fine grind. The SAG mill is then converted to full-autogenous operation, fed by a fully controlled feedsize distribution. This ensures stable long-term operation in AG mode. The AG mill can be pebble ported to feed the pebble mill. The reduction of power from a ball to a pebble mill is based on the HPGR and the AG mill producing a considerable portion of the final product, thus reducing the load on the secondary mill.

Additionally, fine screening can be considered as a replacement for the cyclones. Screens dramatically reduce circulating load by eliminating fines bypass to the coarse product. This further reduces the workload on the pebble mill, in the order of 20%, and produces a flotation feed with less ultra-fines. Less fines in the final product also reduce entrainment of gangue and the drop-off in recovery of ultra-fines in the flotation recovery process.

A further circuit simplification is offered here of installing one of the latest generation 'monster' cone crushers. 1200 kW machines are in production, offering the potential of treating up to 1000 tph in a secondary crushing application.

This circuit layout also offers future expansion by reverting to SAG, then ball mill; hopefully a case never warranted.

Expansion options

The potential waste sorting and coarse flotation options shown in Figure 4 represent a future circuit expansion (circled in coarse dotted lines) of at least 40%, via intelligent processing minus the addition of any more energy-intensive comminution equipment. Thus, a site builds for this, and actively pursues the technology of sorting (with on-site piloting being a relatively straight-forward bolt-on option), as their (lower capital, and considerably lower energy) major expansion option down the track.

The option of dry clay removal offers the potential to dramatically reduce viscosity issues throughout the circuit, by removing clay before it is dissolved into the pulp. This is addressed to some extent in the work of de Kretser, Powell, Scales & Lim (2009). The removal of clay also offers the opportunity to markedly improve water recovery from the tailings.

Coarse flotation provides the scope to remove gangue material prior to fine grinding. Research is underway on effective flotation of material up to 600µm. As over 60% of the comminution energy is required for the final fine grinding, removal of part of this coarser fraction significantly reduces the overall energy consumption.

The three-product cyclone produces a distinctly different middlings product, rich in coarser low-density particles and high-density fine particles; Mainza, Powell & Knopjes (2004). This product should provide an ideal feed to the coarse flotation section.

The potential of sorting excess pebbles to waste is included as in many ores the highly competent pebbles are barren or low in grade.

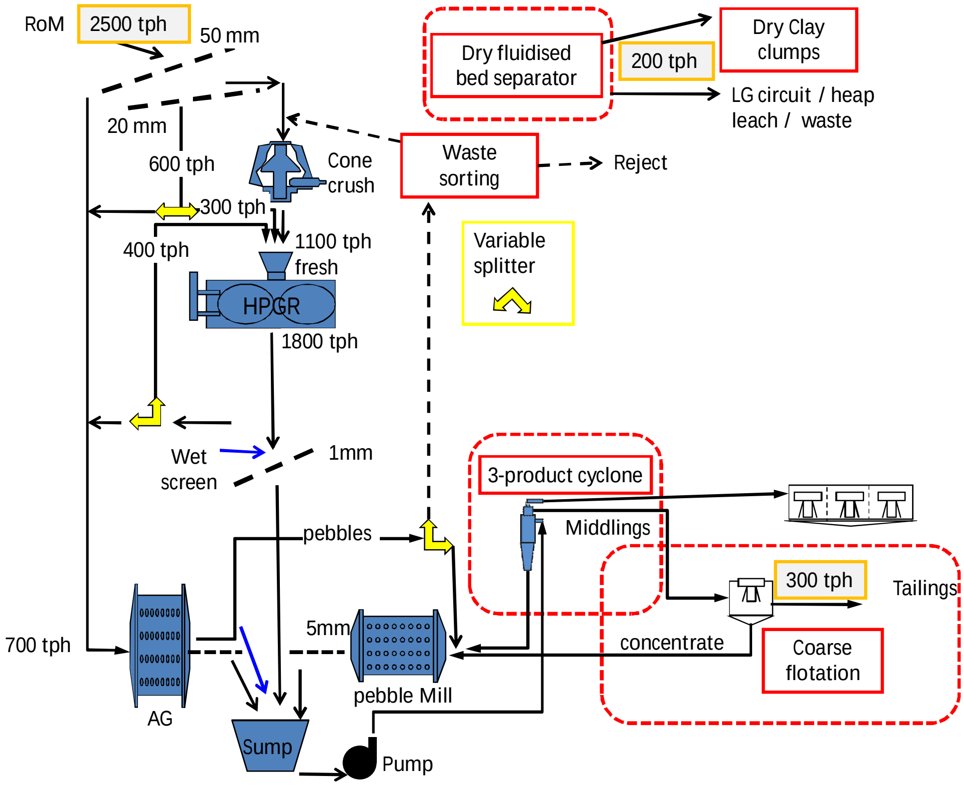

Figure 4 – Possible hybrid HPGR – SAG circuit with future expansion options

The benefit of such a circuit design, from an energy perspective, is the potential to save nearly a quarter of total energy usage with existing equipment; and over 60% energy, with the expansion through sorting and coarse gangue rejection; presented in Table 1. This again indicates the potential for improved recoveries when ore screening and sorting is utilised.

Table 1 – Hybrid circuit with future expansion options scenario energy and recovery outcomes

Scenarios	E, MW	% Energy saving	TOTAL energy with embodied	% TOTAL Energy saving	recovery, %
Base	18.1		25.1	0	85.0
Hybrid	15.8	13	19.3	23	85.0
Hybrid + coarse upgrade	9.9	45	9.9	61	88.1

The Flexible Circuit Design approach challenges current perceptions and trends in our industry. It is intended to create opportunities to utilize more integrated and innovative approaches to enable step changes in mining performance: with regards to energy usage, by dramatically expanding the viable ore-body; with regard to environmental impact, by reducing water wastage and by reducing or eliminating the entry of deleterious elements into the environment; and overall by dramatically improving the usage of our limited resources. In principle these circuits can offer both higher recoveries as well as lower energy usage than the single processing options.

The challenge lies in designing a circuit, mine plan, and blast design, in a holistic manner; so as to be able to dramatically lower the overall cut-off grade of the mine and reduce the overall impact of the mining industry on the environment. This will ensure our continued licence to operate and our sustained profitability in the long-term. The circuit layout also has to be carefully considered to minimise conveying, transfer chutes, storage and materials handling in general.

UPTAKE

The concepts developed in this work are ready for testing via pilot work and intensive simulation studies.

The required integrity of simulation capability is only just coming to fruition, through improved equipment and process models and the early incorporation of multiple ore components in the models. This model evolution is covered, amongst others, in the works of Dundar, Benzer, Aydogan, Powell & Mainza (2011), Kojovic, Powell, Bailey, Hilden & Drinkwater, (2011), Bueno et al., (2011a,b), covering the evolution of the HPGR and SAG models. Multi-component simulation is key to full uptake and utilisation of this methodology in the long-term. This is being addressed in the AMIRA P9 project and by the CRC ORE.

Pilot plant testing of these hybrid circuit concepts, especially the linking of SAG/AG mills and HPGR, and then integrating with upgrade and coarse recovery techniques, is required to prove the efficacy of the proposed processes. It is proposed that these can be integrated with standard process design studies that would involve extensive ore testing and piloting studies.

Improved process control is essential to taking full advantage of the proposed circuits. It is suggested that the design of the control system be integrated with the circuit design, so as to ensure that the design is well-conditioned for stable control, e.g. by reducing the number of interactions and dependencies between equipment. The operational staff must also have a far higher level of training and process understanding than is currently the norm in mineral processing plants.

Integral to control and design is dynamic process simulation. This will be required to simulate the shift of workload across the circuit, as the feed varies daily and over life of mine. A start has been made on this within the CRC ORE. The characterisation of the feed and its variability over life of mine is necessary to be able to simulate the likely operating ranges that will be encountered by the processing plant. This is being addressed in the AMIRA GEM project, and integrated with the flexible circuit programme under the CRC ORE. Simulation of the full range of likely feed scenarios will enable an informed decision to be made on where excess capacity and power are required, as opposed to arbitrarily adding 20% to each piece of equipment. The hybrid circuit design relies on being able to shift the work load between the different components in the circuit and this is where the buffer capacity is contained.

It is proposed that we can build circuits with current technology and certainty of performance, while designing in flexibility for control and expansion, through the take up of new technology as it is developed in the coming years. In the coming years, let us not look back with regret at having built a whole generation of new plants and site expansions, that failed to incorporate and capitalize on the latest technology, both available now and into the future.

The entire concept of this advanced and integrated circuit design has been taken up in the ‘flexible circuits’ programme of work within the CRC ORE, so will be receiving considerable attention and funding over the coming few years.

Leading the way is the expansion that is already under construction at Cadia Hill mines, as described in the work of Engelhardt, Robertson, Lane, Powell & Griffin (2011). This circuit has crushing via two MP1000 cone crushers; an HPGR, with variable speed and edge recycle, feeding the SAG mill; split of RoM ore to stockpile to feed the SAG mill; and the option of diverting HPGR product to a new large ball mill. The circuit has many of the attributes outlined in the examples of this paper; having an ability to control the SAG mill feed size distribution and an option to shift the work between the SAG and ball mill if required.

CONCLUSIONS

Potential benefits to the industry:

- Possible energy reductions of greater than 50%
- Uses current technology while building in access to future technology
- Improved control and consistency of comminution circuits
- Enhanced ability to predict and therefore control comminution performance as variables change, e.g. ore quality, throughput

What needs to be done to reap these benefits?

- Do more than tweak traditional approaches to achieve required step changes in performance
- Use a more sophisticated approach- process integration
- Consider comminution devices in a circuit, not as unit operations
- Grind less and grind coarser
- Shift focus from ore sorting to gangue rejection and ore upgrade
- Carefully engineering the plant layouts to minimise materials handling, storage and footprint.

Pilot plant testing of these concepts (especially the linking of SAG/AG mills and HPGR, and then integrating with sorting techniques) is the next logical step in the development of flexible circuits to ensure the sustainability of our industry.

All these processes provide opportunities for designing with current technology, while allowing for the uptake of future advances in processing capability.

Indeed, flexible circuits – designing and building for the present and the future by allowing for the uptake of new and future technology - may become our design war-cry of the future.

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