Developments in Processing to Match Future Mining Opportunities

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ABSTRACT
Throughout its history the mining industry has focused on the highest-grade deposits sited in the most convenient locations. The burgeoning global population and higher standards of living not only increase the demand for mineral products but also make it harder to mine and process them. The future will include the development of lower-grade, more complex orebodies, and orebodies in difficult locations. The industry will be expected to provide for humanity’s needs while reducing its environmental footprint and maintaining profitability.

This paper reviews some of the likely adaptations in mineral processing that will occur over the next 20 years. The challenges inherent in adapting to lower grade and more complex materials might be exacerbated by such factors as the availability of water and low-cost energy.

In underground mining, higher energy costs are likely to foster further developments in underground preconcentration, especially for ores that can be upgraded at relatively coarse sizes. The adoption of underground crushing could also render material amenable to semi-dry preconcentration options such as might be achieved by the rotary classifier developed by CSIRO and being commercialised by RCR Tomlinson, or more modern versions of the hand-sorting of ore that use sensors based on colour or other suitable rock properties. The cement industry and some gold roasters have used the alternative of dry grinding and classification, which might also have a part to play in dry processing.

There is also likely to be increased interest in options such as in situ leaching that further minimise the surface disturbance.

Underground operations will have to balance the energy savings from reducing the amount of material brought to the surface and reduced surface disturbance against the practical limitations of installing and maintaining processing equipment underground. On the other hand, surface disturbance and energy issues in open cut operations will be balanced by potentially lower mining costs and higher overall recovery from the deposit.

INTRODUCTION
With the depletion of high-grade (easy) deposits, the mining focus is shifting to lower-grade (more difficult) deposits, in less hospitable locations. Even in these locations, and certainly in locations near highly-populated or sensitive areas, there will be increasing pressure to minimise the disturbance footprint of the mining and processing operations, favouring more use of underground mining and in situ extraction techniques where deposits are suitable.

Operating costs in underground mines can be lowered by reducing the amount of material that is brought to the surface through moving some of the processing underground. The minimum amount of material that must be brought to the surface includes the contained metal, the waste initially produced in mine development and the volume displaced by the swell factor as material is mined. Rejection of some of the feed at an intermediate size will also save energy by reducing the amount of material that needs to be ground for recovery processes. Underground preconcentration can also help cope with decreasing ore grades by upgrading the feed so that only higher-grade material needs to be brought to the surface for further processing.

In some parts of the world, the mining industry already has to cope with water shortages. This will foster development and adoption of dry processing techniques, which to date have not been able to achieve the same selectivity as wet processing. Fortunately there are several developments incorporating dry processing that are showing promise. These include multistage high pressure grinding rolls (HPGR), the Commonwealth Scientific and Industrial Research Organisation’s (CSIRO) dry rotary classifier and developments in automated sorting.

An alternative approach to coping with land-access issues is to look at alternative mining locations, such as under the sea. While these have long been pipe dreams, there are at least two ventures now planning to start production from submarine resources over the next couple of years. The miner’s life is likely to be further complicated by increasing energy prices and potential pressures to reduce greenhouse gas (GHG) emissions, both coming when we need to mine and process lower-grade materials that are more difficult to access.

ACCESS CONSTRAINTS
As the public increasingly demands reduced disturbance from mining and processing operations, there is renewed interest in underground mining and in situ extraction techniques on the part of some mining companies. However, there is also significant public concern over protection of aquifers.

The development of large equipment and processing improvements has allowed companies to use open-cut mining to profitably extract the lower grade halos left around historical mines. However, as new orebodies amenable to underground processing are discovered, there is fresh impetus to choose underground mining to try to minimise surface disturbance, especially for deeper orebodies that will incur significant stripping costs for open pit operations and can benefit from the lower dilution that underground mining can deliver. As energy prices increase, the economics will favour more selective underground mining, particularly in areas with low cost labour.

Underground preconcentration might make narrow vein orebodies more amenable to mechanised mining without excessive dilution. This would be achieved by upgrading the material to reject dilution before it is brought to the surface.

Underground and in-pit processing
Processing some of the ore underground would reduce the amount of material hoisted or trucked to the surface. Reducing ore haulage is becoming increasing important as energy costs rise. Placing primary crushing and preconcentration underground will not only save the cost of hauling the rejected waste to the surface, but can also provide a coarser backfill component to enable production of higher strength backfill in the form of concrete containing aggregate, rather than cement stabilised paste. This may be suitable for roof support, rather than needing to leave pillars of unmined ore for roof support.

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In-pit crushing and coarse preconcentration can also be used in open pit mines, with the reject stream going directly to waste rock storage, rather than to the process tailings storage facility.

The target for underground preconcentration might be to reduce the quantity of material that must be hoisted to the surface, to that required to match the swell factor after mining (typically rejection of about 60 per cent of the material underground and only taking 40 per cent to the surface). Bamber et al. (2005) listed the following advantages of underground preconcentration:

- lowering the cost of metal production;
- reducing underground haulage, hoisting, surface transport, milling and tailings disposal;
- lowering the cut-off grade through reduced operating costs;
- increasing the mineral reserve by lowering the effective cut-off grade;
- potentially delivering smelter grade ore directly to surface, thus avoiding the need for a surface concentrator plant (direct shipping ore >25 per cent Cu + Ni; Bamber, Scoble and Klein, 2006a);
- decreasing the selectivity required when mining to avoid dilution, thus increasing productivity;
- possibly increasing the maximum stopping height (ground conditions permitting), allowing more productive mining equipment and the introduction of automated roof-bolters;
- potential changing to bulk-mining techniques, due to the inclusion of a continuous, efficient and effective waste-rejection step within the mining cycle; and
- improving ground control and potentially reducing rock bursting by using better quality backfill in the mining voids.

In colder countries like Canada, shallow subsurface processing facilities are already more common, because they can reduce issues with low winter surface temperatures. A simulation study by Morin, Bamber and Scoble (2004) indicated that up to three days’ surge capacity is required ahead of an underground preconcentrator to enable smooth operation of the whole system from mining to backfilling at a mining rate of 1000 tonnes per day (t/d). Hence there is significant underground development required for such an approach. This could increase capital costs, but the increase would be offset by much lower operating costs. Backfill technology also needs to change to allow the best use of the coarser material produced from underground preconcentration (Bamber et al., 2006b) as aggregate in the backfill mix to increase the strength of the backfill. A simulation study by Bamber et al. (2004) indicated that implementation of underground preconcentration could increase the capital cost of a project by six per cent, with the milling component of capital increasing from around 35 per cent to 47 per cent. However, if preconcentration could achieve 95 per cent recovery into 40 per cent of the mass, this could reduce the overall project operating costs of working with a narrow vein system by 20 - 40 per cent.

The main current technology that could be used for underground preconcentration with coarse lumps (eg 15 - 40 mm) is heavy- or dense-medium separation. Bamber et al. (2005) reported that dense-medium separation systems in lead–zinc applications are able to reject 33 - 74 per cent of the feed. Further crushing or grinding to -14 mm would bring the particle size into the range currently fed to Gekko InLine pressure jigs. Crushing or grinding to -4 mm would make it suitable for conventional jigs. Further comminution to the 50 - 1000 µm particle size range would make the feed suitable for enhanced gravity devices or even coarse particle flotation (up to 400 µm).

However, there are several issues with underground preconcentration. The conventional approaches to preconcentration rely on wet processing, hence water needs to be transported to and from the surface. This is in addition to the minimum quantity of material needed to compensate for swell of the ore. It is technically feasible to use automated sorting systems to reject waste rock at lump sizes coarser than the sizes that dense medium systems can treat, say the 100 - 200 mm size range, but such systems are currently rarely used in the mineral industry.

There are also issues with construction, operation and maintenance of equipment underground, with more people being exposed to risks of working underground. Further work needs to be done to make operation of an underground plant ‘safer’ and ‘more efficient’. Currently, underground operation is not conducive to efficient use of manpower. This makes construction and operation of underground facilities more expensive. Ongoing developments in remote operation may make it easier for much of an underground plant to be operated from the surface, but this still leaves issues with performing maintenance as efficiently as on the surface.

A highly-selective mining approach is probably limited to relatively-high-grade material that can support the cost of underground mining with a low tonnage operation. There are few underground installations of large grinding mills required for multi-million tonne throughputs. Current designs of automatic sorting systems are also generally limited to throughputs of less than 100 t/h per unit, so that multiple parallel units would be required for higher throughputs.

**Gekko python system**

Gekko Systems Pty Limited (Gekko), an Australian company, has developed its Python underground processing plant (UPP) for deposits that are amenable to gravity recovery with or without flotation. This plant is designed to operate in a five metre by five metre tunnel, to produce high-grade concentrate that is pumped to the surface (Gekko, 2007). The system was initially developed for gold ores from which a gravity concentrate can be produced by jigging and enhanced gravity separators, it would also be applicable to other materials that can be concentrated by gravity processing. Its application could be extended by adding a flotation module (currently designed to recover finer gold associated with sulphides), but this will require underground grinding.

An initial 20 t/h prototype was developed to prove the concept. Gekko personnel claim the system offers significant reductions in the costs of haulage, ventilation, backfilling, staffing, tailings disposal and environmental controls. Table 1 from Gekko (2007) shows their estimate of the differences in operating costs (in US$/t of ore) for two mines (A and B), comparing conventional processing with use of a Gekko underground processing plant. In addition to haulage savings, they suggest that there could be significant savings in metallurgical processing by relying on gravity and flotation for gold ores amenable to this approach.

<table>
<thead>
<tr>
<th>Process</th>
<th>Mine A</th>
<th>UPP† A</th>
<th>Mine B</th>
<th>UPP† B</th>
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<tr>
<td>Mining</td>
<td>54</td>
<td>50</td>
<td>90</td>
<td>81</td>
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<tr>
<td>Haulage</td>
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<td>3</td>
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<tr>
<td>Metallurgy</td>
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<td>14</td>
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<tr>
<td>Other</td>
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<tr>
<td>Total (US$/t)</td>
<td>104</td>
<td>79</td>
<td>154</td>
<td>114</td>
</tr>
</tbody>
</table>

† UPP – using Gekko Python underground processing plant.
Gray (2007) pointed out that the Gekko system could reduce power consumption over conventional processing (he estimated an underground installed power consumption of 8 kWh/t with a Python UPP compared with 14 - 16 kWh/t for conventional milling ahead of leaching). The data in Table 1 suggest a potential saving in operating cost of around 25 per cent over conventional processing for ores that are amenable to gravity concentration.

**In situ processing**

Bamber, Scoble and Klein (2006a) have defined three types of **in situ** mining:

1. **solution mining** (eg uranium, salts), where wells are drilled and solutions pumped in and out of permeable sandstone type of aquifers;
2. **in situ** mining (eg copper, gold, base metals), where there is some need for fracturing of orebodies to create the required permeability; and
3. in-stope leaching (eg copper, gold), where there is underground mine development, but at least some of the ore is leached in the stopes rather than being extracted from the mine.

**In situ** processing may be regarded as the ultimate way to minimise surface disturbance. An example is a BHP Billiton Limited copper mine under a cotton field in Arizona (Klein, 1997). However, stopping reagents leaking outside the target area and rehabilitation of the aquifer after mining are significant issues that need to be addressed to allay environmental concerns (Mudd, 2000).

The applicability of **in situ** leaching (solution mining) is limited to deposits with the required ore permeability and chemistry in a suitable hydrogeological setting. Ideally one needs an orebody within a saturated permeable sandstone matrix with impermeable barriers around it, in an aquifer that will not be used for beneficial uses and is not connected with other aquifers that have potential beneficial use. **In situ** leaching has been applied to uranium extraction using both acidic and alkaline lixiviants, depending on the host rocks and ore mineralogy. It has also been applied to copper extraction using acid solutions, but most of the copper applications can better be described as in stope leaching associated with underground mining.

There are currently two **in situ** uranium extraction operations in Australia, at Honeymoon and Beverley, both using acidic extraction systems as the aquifers are naturally acidic. Where the ore contains significant quantities of carbonate, acidic leach solutions are not an economic option and alkaline systems are used. In 2000 there were five **in situ** uranium extraction operations in USA using alkaline (bicarbonate-based) extraction systems that accounted for around 92 per cent of US uranium extraction (Mudd, 2000).

**DRIY PROCESSING**

Reducing the dependence on water, or developing alternative water sources, is required to overcome constraints to copper production in Northern Chile (BHP Billiton Base Metals, 2007) and China (Carroll, 2007). The Australian Mineral Research Association (AMIRA) has recently been seeking to broker a project to investigate several dry processing technologies that might be applicable to the copper industry (Fraser, 2007). Potential devices include the CSIRO rotary classifier and sorters developed for the coal industry.

**Ore sorting**

Our ancestors practised hand sorting of rocks since the dawn of mining. This became impractical as the richer mineral deposits were exhausted and the costs of labour increased. However, photometric automated sorters have now been used for several years. These systems offer a way to cope with lower feed grades and they can reduce comminution energy requirements by rejecting more material of larger sizes.

Automated sorting can use properties that can be measured by non-contact means, such as photometric properties, magnetic susceptibility, X-ray transmission, or radiometric emission or absorption. Commercial units available from CommoDaS GmbH in Germany or Australian companies such as Applied Sorting Pty Limited (Applied Sorting) and Ultrasort Pty Ltd. The basic electronics, optics or other detection systems, and pneumatic ejection systems have been proven in automated sorting applications in other industries, so that these units can offer reliability and ease of maintenance. The feed to these units needs to be screened to remove fines, as the minimum particle size is set by the resolution of the detector system and the spacing of the ejection air jets.

Ultrasort has commercial electromagnetic sorters in use on nickel sulfide ore at Consolidated Mines Kambalda operations (Ultrasort, 2008) processing 20 - 70 mm material at up to 60 t/h, with other units proposed to process material down to 6 mm and from 40 - 300 mm material at up to 250 t/h. The units are applicable to ores and smelter slags with suitable electromagnetic differences from the waste. It also has units based on radiometric sorting in use in the uranium industry in southern Africa.

X-ray transmission offers another avenue to assess lumps of ore, rather than just the properties of the surface layer. Depending on the manufacturer, current X-ray transmission sorting system can process particle sizes between five and 150 mm at feed rates up to 40 - 100 t/h. The technique is applicable to ores where the mineralisation occurs as particles or lenses within the rocks.

Applied Sorting (2008) reported that tests performed with a pilot scale X-ray transmission unit on Vital Metals Limited’s scheelite ore have demonstrated that its system can achieve 55.2 per cent rejection of the feed material with a tails grade of 0.027 per cent WO3. The system is said to be applicable to elements such as molybdenum, vanadium, nickel, manganese, tin, bismuth and tantalum. It is likely that mineral discrimination will continue to improve with advances in technology in a similar way to developments in photometric sorting, where discrimination has improved with increased computing power, enabling the number of wavelengths scanned simultaneously to increase from less than ten to over 200.

Any approach that can measure changes in bulk physical properties that are related to the valuable metal content of lumps of ore can, in theory, be used and there is the potential to combine different approaches to improve selectivity. While in some cases mineralisation is coarse enough to enable effective preconcentration of lumps, finer grained minerals will require further crushing so that conventional gravity treatment, or even coarse particle flotation, will be the most effective (wet) preconcentration options. Canadian studies have examined the potential for underground processing based on such coarse-particle technologies as: optical sorting, conductivity sorting, high-intensity magnetic separation, gravity separation or dense-medium separation, targeting 95 per cent recovery with 60 per cent rejection at a particle size of 100 per cent minus 80 mm (Bamber et al, 2005).

**Dry grinding**

High-pressure grinding rolls are an emerging technology for dry grinding in the hard rock process industry. These units have been used for over 20 years in the diamond industry for crushing hard rock and for longer in the cement and clinker industry for fine grinding using air classification. The energy efficiency of
commercialisation using HPGR in copper ore processing plants is emerging as a significant advantage over the more conventional circuits using semi-autogenous grinding (SAG) mills (Lane and Fleay, 2002; Dunne et al, 2004; Maxton, Morley and Bearman, 2003).

Various researchers and practitioners are now considering the potential advantages of multistage HPGR circuits to grind to product sizes that approach those suitable for gravity processing (<2 mm) and possibly flotation.

The principal challenge for dry grinding circuits is the need for dry classification and effective control of product size. This requires the use of heat to dry the ore and energy to run the materials transport and air classification systems.

Dry processing might require grinding as part of the feed preparation. The cement industry has developed grinding and classifying systems that rely on air rather than water. These include vertical roller mills of the type manufactured by German companies Loesche GmbH of Düsseldorf (Loesche, 2008), and Polysius AG of Neubeckum (Polysius, 2008) and classifiers that use spinning tables and vanes to segregate particles of different sizes (eg Polysius, 2008a).

Newmont Mining Corporation (Newmont) and the Barrick Gold Corporation (Barrick) have installed Polysius’s double-rotator dry grinding mills and air based dynamic separators in their roaster operations in Nevada (Thomas, Cole and Williams, 2002) and at Minahasa in Indonesia. Newmont and Barrick selected dry grinding and classification to avoid the need to evaporate water ahead of roasting low sulfide content gold ores. There are still, however, energy requirements to completely dry the ore ahead of grinding and to supply the air for classification. The ore at Barrick’s operation contains about 1.9 per cent sulfide sulfur and 1.45 per cent total carbon, so there is insufficient available energy in the ore to roast it autogenously (Buckingham et al, 2001).

Thomas, Cole and Williams state that ‘the grinding costs of wet and dry grinding plants are very similar’.

Buckingham et al reported throughputs of up to 315 tonnes (350 short tons) per hour of ore.

The CSIRO dry rotary classifier

Conventional air classifiers and hydrocyclones are able to separate out coarse and/or dense particles from the finer, less dense, ones. CSIRO has developed a dry rotary classifier that is able to concentrate the smaller particles along with the dense ones to provide an alternative approach to concentration. The technology is currently undergoing commercialisation by RCR Tomlinson Limited (RCR) at the 10 t/h scale. The unit is reported to offer low power consumption, low noise, no dust production and low wear with potential to be scaled to operate at a range of particle sizes (Liffman, 2008).

Figure 1 (Liffman, 2008) illustrates the basic principles of the CSIRO classifier. The rotation of the classifier imparts a cascading flow to the particulate material within the device. This movement causes segregation, with the smaller and denser particles migrating to the centre of the cascading material. The unit’s size separation ability could offer a more compact approach than conventional screens. The challenges have been to engineer consistent segregation and stable extraction of the concentrate from the classifier, such as with vibrating extraction tubes. It has been claimed that the unit may offer a solution to blinding of conventional screens.

Development work is also seeking to define the minimum number of classifiers required to achieve any particular product purity. Unlike previous gravity separation devices there is, in principle, no limit to the size of the particles that can be separated. Research has suggested that the maximum particle size should be around one fiftieth of the diameter of the rotating cylinder, with perhaps a lower limit at 100 μm (Liffman, 2008).

Hence, scaling up the diameter of the cylinder can allow processing of larger particles.

There might be synergies between the drying, grinding technology described in the previous section and the CSIRO–RCR rotary classifier at sites where water is in short supply. The drying, grinding and classifying technology could be used to liberate the valuable minerals from gangue minerals and to present more uniform size distributions to banks of rotary classifiers that could concentrate the minerals before shipment.

UNDERSEA MINING

One way to sidestep restrictions on access to onshore deposits is to follow the example of the oil and gas industry and look at offshore deposits, though based on US oil experience there can also be access issues with such developments. Submarine mining also opens the prospect of accessing the 71 per cent of the earth’s surface that is beneath the ocean’s surface. It has so far been limited to near shore tin or diamond deposits, but over the years there has been continuing interest in seafloor mineral deposits. Interest in the 1960s and 1970s was mainly focused on manganese nodules, particularly in the area in the equatorial Pacific known as the Clarion-Clipperton fracture zones (Glassby, 2000). As the name implies, these nodules are rich in manganese (27 - 30 per cent). They typically also contain 1.1 - 1.5 per cent nickel, 1 - 1.3 per cent copper and 0.2 - 0.4 per cent cobalt (Hammond, 1974) and most occur at depths greater than 1 km. Metal extraction was deemed to be uneconomic at 1970s metals prices and the reported mining trials with the Glomar Explorer were later revealed to have been a CIA cover for operations to recover a sunken Soviet submarine (Glassby, 2000). While nickel prices are now higher than they were then, processing of onshore laterite ores with similar nickel grades is likely to be able to satisfy current nickel demand without the resort to deep sea mining.

Two companies, Nautilus Minerals Inc (Nautilus) and Neptune Minerals Plc (Neptune), have plans to commence mining Pacific Rim seafloor massive sulfide (SMS) deposits created by volcanic activity near Papua New Guinea (PNG) and New Zealand. Both companies have been able to attract support from major mining interests, which demonstrates that the industry now views these proposed developments seriously. Nautilus has carried out subsea electromagnetic exploration for copper, gold, zinc and silver deposits around PNG, Solomon Islands, Fiji, Tonga and New Zealand. It plans to start production in 2010 at its Solwara 1 deposit between New Britain and New Ireland off the coast of PNG. At a four per cent cut-off grade, the deposit has inferred resources of 1.3 million tonnes (Mt) at 7.5 per cent
copper, 7.2 g/t gold, 37 g/t silver and 0.8 per cent zinc (Lipton, 2008). Neptune is planning to start trial mining of its Kermadec tenement off the north coast of New Zealand in 2010. It is located just outside the 200 km territorial zone. Neptune’s projected costs are somewhat higher than those of Nautilus due to increased depths and distances to shore.

Advantages claimed for this approach are limited mining infrastructure, limited social disturbance, minimal overburden stripping, increased mine worker safety (as all mining personnel remain in the surface vessel) and reduced mining waste due to the high-grade nature of the deposits. A specially-developed seafloor mining tool will be required to cut and pump the mineral material to a surface vessel, where the slurry will be dewatered before being barged to onshore storage at the proposed treatment facility. Metallurgical test work has confirmed that conventional flotation processing can produce a marketable concentrate from what is essentially a chalcopyrite ore. The projected capital costs for two seafloor miners and associated equipment have been reported at US$120 million, with an Ausenco-estimated capital cost of US$153 million ± 35 per cent for the conventional onshore concentrator plant Toyne (2008). He also reported projected mining costs of US$80/t to deliver the ore to the concentrator, with a further US$14/t for concentrator operation.

Preliminary indications are that onshore processing of the ore will vary little from conventional ores. The main challenges will come from development of the novel seafloor mining equipment, operation of the dewatering system and return of water to the mining zone while minimising disturbance to the mining zone by silt or fines, to allay environmental concerns. On-vessel screening and dewatering of the slurry pumped from the undersea cutter will also be conventional apart from taking into account the low temperature of the deep ocean water.

**APPROACHES TO DEAL WITH MORE COMPLEX ORES**

Some of the more complex ores require finer grinding before the valuable components can be adequately liberated for recovery. This has fostered the development of several energy intensity stirred-grinding technologies. Vertical stirred mills offer a higher energy intensity and higher grinding efficiency at smaller particle sizes than conventional ball mills. The horizontal IsaMill™ has developed the stirred grinding concept further, offering even higher energy intensities, to make it easier to retrofit into existing circuits where space is at a premium. Pease (2007) discussed the advantages of the IsaMill™ approach based on energy efficiency as a function of medium size and also discussed the process benefits of using an inert medium demonstrated at several base and precious metal operations.

**APPROACHES TO MINIMISE ENERGY REQUIREMENTS**

There will be an increasing requirement to design processing plants for energy efficiency. It has been estimated that 50 - 85 per cent of the energy required for metal extraction is used in the comminution stage of the process (US Department of Energy, 2001; Tromans, 2002) and comminution consumes about three per cent of the world’s energy (Pease, 2007). The combination of energy and materials required for comminution (liners, grinding balls, etc) typically account for around 50 per cent of the operating cost of a mineral processing plant (Fuerstenau, 2003). Hence, improvements in comminution energy – through the application of HPGRs and/or IsaMill™, for example – will receive increased attention as energy costs increase.

The recent concerns about emissions of carbon dioxide and other GHGs will result in increasing pressure on the mining business to develop and apply energy-efficient alternatives to current mineral processing routes.

The obvious commercial reality of pressures to reduce GHG emissions in power production will be increased electrical power costs. The less obvious outcomes are higher costs for equipment, construction materials, transport, labour, and other components of mine and process plant project development. Energy efficiency improvements are brought about by producing the same or better outcomes or outputs with lower energy use, ie adding value to each energy unit.

Ausenco approaches energy efficient design in three ways:

1. improving process selection and design,
2. optimising engineering design and plant layout, and
3. operating power and materials consumption.

Energy efficiency improvement can be measured in a number of ways, including:

- reducing electrical energy consumption per unit of production,
- reducing effective carbon dioxide emissions per unit of production, and
- optimising net present value (NPV) by considering operating and capital costs based on market predictions for energy sensitive commodities.

In many ways, the NPV approach to energy efficiency is the most pragmatic and acceptable business model to adopt. This approach captures the energy efficiency component in the projected cost of energy and consumables and measures the outcome in terms that are acceptable to managers and financiers.

**Process selection**

As noted above the majority of energy in the mineral processing industry is consumed in comminution, the process of breaking ore into particles small enough to separate the value material from the gangue material. The subsequent separation can be through a physical process where the particles are separated according to their physical properties (gravity or flotation response); chemical processes where they are leached and then recovered from the solution; pyrometallurgical processes where the components are separated in a molten state; or a combination of all three processes.

The comminution process efficiency or inefficiency is magnified in the downstream process energy consumption. Energy is also consumed in:

- producing the grinding medium,
- manufacturing reagents for the flotation or leach circuits,
- manufacturing and operating pumps and flotation cells,
- producing and installing the steelwork and maintenance materials,
- metal recovery (eg electrowinning and smelting), and
- separating impurities.

Inefficiencies in comminution generally lead to increased downstream costs due to increased levels of impurity in the intermediate products or reduced recoveries.

Improvements in process design at Ausenco are focused on:

- working with mine blast designers to optimise blast design and achieve optimum fragmentation for mine materials handling and maximum energy efficiency (blasting is generally more energy efficient than crushing and grinding in the process plant);
- exploring opportunities to use high pressure grinding rolls in comminution circuits to replace less energy efficient conventional crushers and SAG mills;
• evaluating circuits with reduced or no steel grinding medium; and
• optimising the fineness of grind to achieve optimum economic return (recovery trade-off versus cost).

Further optimisation of the energy requirements in mineral extraction require consideration of the complete processing picture, rather than just seeking to optimise single unit operations, ignoring downstream issues that might be created by energy savings in grinding, or preconcentration (Pease, 2007). He points out that if the effects on grinding are ignored in assessment of energy savings in blasting, overall energy may actually increase. Similarly the implications of concentrator optimisation need to be assessed in terms of the impact on smelter operation. Impurities need to be removed at the processing stage that offers the lowest overall energy cost to fully optimise processing efficiency.

CONCLUSIONS

Throughout its history the mineral extraction industry has exhibited a high degree of innovation. It has had to do so that it could exploit new and more difficult resources as easier ones were exhausted. The industry will have to adjust to processing even more complicated deposits in less hospitable environments, compounded with population and environmental pressures that will put more scrutiny on the efficiency of resource use and restoration of the environment after mining. These pressures will result in a reordering of the cost drivers that define profitable metal extraction and may foster new processing routes and locations. Difficulties with land access may force further interest in underground mining and, perhaps, stimulate undersea mining (analogous to the oil industry’s move offshore) as suitable mining technology becomes available.

Individual unit process optimisation has given way to a Mine to Mill approach and is likely to continue to move further to Mine to finished product, full cradle to grave life cycle analysis optimisation. This is the ultimate way to define the most efficient processing routes to supply humanity’s appetite for minerals and gain approval from all relevant stakeholders.

In some regions, shortages of basic processing requirements such as water are already providing drivers towards dry processing. This is encouraging a fresh look at technologies that can provide routes to dry concentration, such as the dry rotary classifier that CSIRO has been developing, or automated sorting processes. The latter have become more practical with easy availability of increased computer processing power, allowing real time detection, analysis and sorting.

Increasing energy prices and concerns over GHG emissions are already favouring more energy efficient processing. Underground or in-pit preconcentration techniques that can operate at coarse particle sizes will reduce the amount of material that needs to be ground before the valuable components can be effectively concentrated for recovery. Automated sorting processes based on magnetic, X-ray transmission or radiometric sorting can supplement photometric sorting to enable effective upgrade at lump sizes. This can build on sorting technology developed in other industries and may well have a significant role to play in preconcentration.

Energy costs are also driving more efficient comminution routes. These can incorporate such equipment as high pressure grinding rolls instead of the traditional multistage crushing approach at the coarser end of comminution, or such developments as the IsaMill™ at the finer end, to provide more cost-effective approaches.

However, none of these drivers suspends the need for free-market players in the mining industry to be profitable. If the new approaches increase the overall cost of production, there will have to be a concomitant increase in the real prices of metals to justify the development of the mineral deposits that require their introduction.

REFERENCES


