INTRODUCTION

Ore sorting and coarse gravity concentration are two of the oldest processing methods employed in the mining industry to beneficiate ores. With the rise of fine processing technologies they have suffered a loss in popularity. With orebodies now being of higher complexity and lower grades, coupled with increased commercial and environmental pressures, an opportunity to revive these techniques to improve overall mine profitability has arisen.

Direct smelting of ores to produce metals was once common practice, however, declining head grades and orebodies that are increasingly difficult to mine has given rise to the need to concentrate the ore prior to this final stage of processing. With the advent of the flotation process and CIL/CIP in the early 20th century, there has been a push towards fine (<150 µm) processing for many gold and base metal ores. Reducing the whole of the ore to a fine size is energy intensive, so decreasing the amount of material that needs to be taken to a fine size can lead to major energy savings. Adding an additional preconcentration step and rejecting waste material prior to final size reduction can lead to major savings. A graphical representation of these steps in flow sheet development can be seen in Figure 1.

Traditionally, most of the ore processing operations at any mine site are conducted in processing facilities located on the surface. Given this paradigm it is surprising to note that it is not uncommon for the first stage of processing in mining operations to be conducted underground. There are, however, exceptions to this rule (see Dominy et al, 2009; Klein et al, 2003; Ilgner, 2001). Primary crushing and screening of ore is commonly conducted underground in many modern operations to assist with ore transportation to the surface, so why should adding a coarse separation stage underground be a major leap of faith?

Advances in the robustness and modularisation of processing technology (Hughes and Cormack, 2008; Dominy et al, 2009) over recent years have made it possible not only for separation processes to be conducted underground but for the processing plant to fit into conventional development spaces without the need for additional excavations. They are also capable of being moved as the drive advances to maximising the benefits of preconcentration.

This paper outlines how underground preconcentration using ore sorting and coarse gravity processing can be employed to maximum benefit in the context of a narrow-vein mining scenario. It also details the steps required at the front-end of a project to see if this potential exists.
PRECONCENTRATION

Preconcentration is a process where waste material is rejected allowing down-stream processing to be undertaken on a smaller, richer stream of material. Eliminating waste material at the coarsest size possible maximises these benefits. As orebodies become more and more complex, the infrastructure and operating cost associated with fine whole ore processing becomes prohibitive rendering some projects unviable. Adoption of a preconcentration process that can be conducted at a coarse size thus reducing the amount of material that needs to be taken to a subsequent fine processing stage may tip the balance in favour of project going ahead or even extend the life of an established operation.

Benefits of preconcentration have been reported widely across the literature including Gray et al (2011), Denysschen and Wagner (2009), Bearman (2007) and Klein et al (2003). These benefits include: reducing cut-off grade, increasing mining rate, reducing overall plant footprint, extending mine life, reducing processing costs and reducing energy usage. The benefit obtainable depends in large on the nature of the ore, particularly on its ability to be effectively separated from the gangue minerals present at a coarse size.

PRECONCENTRATION IN A NARROW-VEIN SCENARIO

There are a number of advantages to performing preconcentration underground in a narrow-vein mining situation. These include:

- Reduction in total comminution energy requirements (lower carbon footprint) as some of the waste is removed at a coarser size early in the process route.
- Reduction in tramming and hauling costs both underground and prior to surface processing, due to lower tonnage being moved. Part of these savings will be in the energy required during transport. Others will be from reduced wear and tear on equipment.
- The ability to benefit from use of alternative ore transportation technologies such as hydraulic hoisting (Francis, Turner and Larder, 2005).
- Ability to change to more productive bulk mining techniques, as waste can be rejected earlier on (with obvious impacts on mine life and cut-off grade).
- Improvement in mine call factor, due to smaller stockpiles and potentially fewer stockpiles on route to plant.
- Potential for improved ground control and decrease in rock-bursts, due to the production of an improved backfill (Bamber et al, 2004).
- Potential for improved backfill availability, due to less reliance on surface plant and shorter supply lines (Thomas, 2006).
- Reduction in surface footprint of processing facilities.

Ultimately, the benefit of underground preconcentration is to shift the cost structure of the operation to a more favourable regime. To maximise benefit from preconcentration in a narrow-vein scenario the best place to install the preconcentration plant is underground, as close to the mining face as possible, while including a backfill system as part of the plant. An example of such a plant can be seen in Figure 2. Studies undertaken by various groups, Bamber et al (2005) and Hughes and Cormack (2008), have estimated that by employing underground preconcentration methods, there is a potential savings of 20 - 40 per cent of mine operating costs.

To maximise the benefit derived from underground preconcentration it is necessary to have the plant as close to the mining face as possible. To maintain this throughout the life of mine the plant would need to be movable and ideally not need any special excavation prior to installation. It is thus important to select a processing technology that can be successfully modularised, yet maintain its full functionality. Klein et al (2003) notes that while technologies such as dense medium separation have high separation efficiency they require a significant amount of space for media recovery circuits so they may not be ideal for this application. Simple robust technologies such as ore sorters and the In-Line...
Pressure Jig (IPJ) are robust and require little external infrastructure to operate, which makes them ideal for underground preconcentration.

Lloyd (1979) notes that due to increasing underground costs, as mines go deeper there may be merit sacrificing some process efficiency (eg recovery loss) to reduce the more significant costs associated with mining and haulage. Alternatively if the economics of the project are recovery dependant it may be possible to combine technologies to maintain efficiencies by harnessing the best separation properties of these technologies. Sorting followed by coarse gravity separation are two technologies that could be potentially applied in this scenario. Another example is in Gekko’s modular underground processing plant which utilises coarse gravity separation and coarse flotation technology to maximise valuable recovery. The complementary nature of these technologies can be seen in Hughes, Donaldson, and Murphy (2010) where the IPJ performs gravity separation on the material in the circulating load of a fine crushing circuit and any material that is too fine for efficient separation by the IPJ is scavenged by flotation.

Even if the ore should prove amenable to preconcentration a number of challenges still exist in combining mining and underground processing operations. Many of these issues relate to the integrating of the processing facilities into the mine development and production schedules. Studies have been conducted by Klein et al (2003), Morin, Bamber and Scoble (2004) and Bamber et al (2005) addressing many of these issues by simulation of the integrated process. Lane, Fountain and LaBrooy (2008) make the observation that if wet processing methods are to be employed, the availability and management of water underground could be a major issue in some mines. None of the issues highlighted are insurmountable, especially when the potential payback of underground preconcentration is considered. It should be noted that these challenges will all require an interdisciplinary approach by mining, metallurgical and geological personnel to reach a successful resolution.

PRECONCENTRATION TECHNOLOGY AND TESTING

Ultimately the mineralogy of an ore determines the potential for preconcentration and the suitability of a processing technology. There are a number of technologies that are suitable for coarse preconcentration including: dense medium separation, jigging, ore sorting, coarse flotation, magnetic separation and size separation. As pointed out by Klein et al (2003) the mineralogy of the ore determines the potential for preconcentration as well as the most suitable processing technology. Examination and testing of an ore for its potential for coarse preconcentration is essential for identifying the optimal mine-to-mill flow sheet. It should be noted that coarse preconcentration techniques may not be suitable for all ores.

Ideally, the first step of any metallurgical test work regime is to look at the ore and see if there are any obvious properties that can be exploited. The potential for cross disciplinary cooperation to add benefit to the project exists, as typically the best source of information on whether or not there is potential for coarse preconcentration is the project geologist. Discussing the different ore domains and the occurrence of the valuables (and indeed gangue) in these might highlight not only potential for coarse processing but may also point to the most likely route. For instance, if gold is being targeted and it is situated in a quartz vein that is located in a shale host rock, a sorting application to reject any of the shale hanging wall or foot wall mined from the quartz may have potential to provide an upgrade at a coarse size. The likely next step would be to assess if sufficient liberation exists to allow clean separation of the quartz and dolomite after a coarse crush.

The current trend in metallurgical testing routes involve grinding the ore fine (<150 µm) before testing beings. Once this has been undertaken the sample suitable for preconcentration is gone and the opportunity to test beneficication processes at a coarse size is lost. It is thus essential that the early round of metallurgical testing includes some assessment of the ore’s ability to be preconcentrated prior to the ore being crushed and ground down to finer sizes. Even if the sample is limited performing size-by-grade analysis (after visual inspection) on the ore at various crush sizes may show that there is sufficient liberation to justify further coarse separation test work. Another issue is getting sufficient sample at a coarse size to be representative of the domains of the orebody that are going to be treated. It is advisable that the sample size and the grade of minerals that are being chased be considered to ensure that sampling theory is adhered to. Once again working closely with the project’s geologists is essential to ensuring that the maximum value and information can be extracted from limited samples.

ORE SORTING

Ore sorting is a technology which has proved itself in many installations worldwide. It makes use of a variety of electronic sensors combined with high speed processors that can be programmed to recognise certain characteristics like colour, density, conductivity, etc. A mechanical ejection system is then activated by the processor, which will eject individual particles from the feed stream. These principle components are illustrated in Figure 3.

A variety of sensors measuring material characteristics within the electromagnetic spectrum are available today, as can be seen in Table 1. The latest technology can combine the information from any combination of sensors and thus gather more data about the particles than a single sensor can. For example, by combining an XRT sensor’s signal with that of a 3D laser scanner, particles can be separated from one another based on both density and the rate of refraction of light within a particular mineral.
X-RAY TRANSMISSION

X-ray Transmission (XRT) is probably one of the most versatile types of sensors; it can be widely used in narrow vein mining applications where there is a difference in density between the vein and the host rock. It measures amount of X-ray radiation absorbed within individual particles and negates the effect of particle size by measuring the radiation at two different energy levels.

OPTICAL (COLOUR OR LASER)

Optical material recognition has been around for quite some time but the latest advances open up a wide variety of new applications.

By combining 3D laser object positioning systems with CCD colour cameras, it is possible to separate particles based on colour without the necessity for a non-reflective background, which was practically only achievable by having particles in freefall in front of a black background as in earlier systems. This means that particles can now be sensed and recognised while travelling on a belt at much higher speed and separated with greater accuracy.

INDUCTION SENSOR

Induction sensors use pulsed eddy currents (PEC) to measure a particle’s relative conductivity. The sensitivity of these machines can be adjusted very accurately to target a preset level of conductivity of individual particles. They are used mainly for conductive minerals ores such as nickel, copper and placer gold deposits. They have very successfully been used in old gold tailings dumps (see Figure 4) and should be readily adaptable to a narrow-vein scenario where there are coarse mineral assemblages with a large differences in conductivity.

TESTING REQUIREMENTS

In order to determine the viability and efficiency of sensor based sorting of different ore types, comprehensive test work on individual ore types have to be conducted. Testing will take place in three stages.

<table>
<thead>
<tr>
<th>Electromagnetic wavelength (m)</th>
<th>Sensor type</th>
<th>Material property detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma-radiation</td>
<td>RM (Radiometric)</td>
<td>Natural Gamma Radiation</td>
</tr>
<tr>
<td>X-ray</td>
<td>X-ray transmission (XRT)</td>
<td>Atomic density</td>
</tr>
<tr>
<td>Ultraviolet (UV)</td>
<td>COL (CCD colour camera)</td>
<td>Reflection, brightness, transparency, shape</td>
</tr>
<tr>
<td>Visible light (VIS)</td>
<td>Photometric (PM)</td>
<td>Monochromatic reflection/absorption</td>
</tr>
<tr>
<td>Near infrared (NIR)</td>
<td>Near infrared spectrometry (NIR)</td>
<td>Reflection/absorption</td>
</tr>
<tr>
<td>Infrared (IR)</td>
<td>Infrared camera (IR)</td>
<td>Heat conductivity, heat dissipation</td>
</tr>
<tr>
<td>Microwaves</td>
<td>MW-IR (heating with IR)</td>
<td>Metals heat faster than other minerals</td>
</tr>
<tr>
<td>Radio waves</td>
<td>Electro-magnetic sensor (EM)</td>
<td>Conductivity</td>
</tr>
<tr>
<td>Alternating current (AC)</td>
<td>Conductivity</td>
<td></td>
</tr>
</tbody>
</table>

FIG 4 - Examples of gold recovered from placer tailings by an induction sorter.

Stage one of testing will determine which type of sensor will differentiate most effectively between the reject ore and the target material. Approximately 20 L of material needs to be supplied where the sample has been handpicked to provide approximately equal amounts of target material and reject ore. This sample should be crushed to a size that will allow for the rejection of gangue from ore and will be used to calibrate the sensor and determine viability of separation. Once this stage has been completed a recommendation can be given on whether or not further work is warranted. An example of the output of this stage of the assessment program can be seen in Figure 5.

Stage two of testing will determine whether effective upgrading and separation can be achieved in the desired size range using the type of sensor selected. This step requires
approximately 100 L of representative sample in the desired size range (to be determined beforehand by mineralogical analysis). Assay records are to be done before testing. Using the calibration setting determined in stage one, the sample will be subjected to separation by the selected sorter. The results will be photographed and product/reject streams will be assayed again.

The third and final stage of testing will determine the maximum feed capacity without compromising on separation/upgrading efficiency. Further sample, 200 - 1000 L of dry, representative sample is required and will be subjected to separation by the selected sensor at various feed rates to determine the maximum feed rate that will not affect separation efficiency. This testing is typically conducted on a pilot scale sorter.

**COARSE GRAVITY SEPARATION**

Gravity preconcentration involves concentrating the valuable mineral or rejecting waste ore based on the differences in the specific gravity of the minerals present. Gravity processing is one of the oldest forms of minerals processing which has fallen out of favour in recent years with the push toward fine mineral processing technologies. There are numerous technologies in existence that are suitable concentration of minerals based on specific gravity differences at a relatively coarse (>1 mm) size, these include jigs, spirals and even medium separators.

The Gekko IPJ is a modern take on a tried and tested gravity separation device, more importantly its compact nature lends itself to modularisation and underground installation. Table 2 shows the size, throughput and power requirements of the IPJ. Traditionally jigs have been used to separate relatively coarse particles at relatively low specific gravity differences. A jig operates by expanding a hindered settling bed of the material, so that heavier particles work their way toward the bottom of the leaving the lighter particles at the top of the bed. Fine tuning the separation is achieved by controlling the length and frequency of the mechanical pulsation stroke. The IPJ utilises its own strength and weaknesses. It is important that anyone embarking on a characterisation program has an appreciation of these and designs the program accordingly.

Various methods exist for these characterisation tests, each having their own strengths and weaknesses. It is important that anyone embarking on a characterisation program has an appreciation of these and designs the program accordingly.

The result from the characterisation test work is typically presented in the form of a yield recovery curve, showing how much mineral can be concentrated into a given percentage of feed mass. An example of two typical yield recovery curves can be seen in Figure 6. Sample A is typical of an ore that has shown itself to be amenable to valuable mineral preconcentration. It has a very high recovery of valuable mineral (90 per cent) and rejection to be performed where a recovery of greater than

![Image](https://example.com/image.png)

**FIG 5** - An example output from the initial testing phase. False colour image of five different handpicked ore samples, scanned with an X-ray transmission scanner. The items marked with a border were recognised as ‘wanted’ material by the applied algorithm.

<table>
<thead>
<tr>
<th>Specifications for different models of the Gekko In-Line Pressure Jig.</th>
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<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Cone diameter (mm)</td>
</tr>
<tr>
<td>Unit height (mm)</td>
</tr>
<tr>
<td>Max operating pressure (kPa)</td>
</tr>
<tr>
<td>Maximum throughput (t/h)</td>
</tr>
<tr>
<td>Maximum particle size (mm)</td>
</tr>
<tr>
<td>Minimum hutch water addition (t/h)</td>
</tr>
<tr>
<td>Power (installed) (kW)</td>
</tr>
</tbody>
</table>

**TESTING REQUIREMENTS**

Determining whether an ore type is amenable to coarse gravity separation at a given size is the first step in determining if gravity preconcentration is an option for the ore. As mentioned previously, there are a number of different processing options for coarse gravity separation. Fortunately the testing requirements for all coarse gravity methods in the early stages of orebody development is focused on the characterisation of the ore rather than focusing on machine specific testing. Various methods exist for these characterisation tests, each having their own strengths and weaknesses. It is important that anyone embarking on a characterisation program has an appreciation of these and designs the program accordingly.

Aresenopyrite, gold), Goldfield SA Kloof Python (aresenopyrite and gold) and Silver Standard’s Pirquitas Mine (lead, silver and tin minerals). These and other examples can be found in the literature (Gray et al, 2011; Dominy et al, 2009 and Hughes et al, 2008).
95 per cent of the valuable can be achieved by rejecting 25 per cent of the material at this size. A curve (not shown) with a slope close to 1:1 when plotted on a yield recovery curve would indicate that the mineral was not amenable to gravity concentration. The final determinate of the ore’s suitability to coarse gravity separation is the economics of the proposed design which can be examined in detail once this data exists.

Historically heavy liquid separation (HLS) has been used to separate minerals in a sample into different density fractions. Typically the minerals were placed in the high specific gravity organic liquid and then the sinks (material of higher specific density) and floats (material of lower specific density) were collected. This process was then repeated with a liquid of a lower density, typically a dilution of the original liquid, until the sample is fractionated into sinks and floats over a wide range of specific gravities. A yield recovery curve can be constructed from the resultant data. Unfortunately the liquids commonly used such as Tetrabromoethane are highly toxic and their use is being phased out due to health concerns.

Alternate methods of characterisation to HLS can be achieved using dense medium characterisation process such as pilot dense medium cyclones and Gekko’s Viking Cone. The size of the laboratory facilities and equipment available will limit the size ranges where each of these characterisation tests can be performed. As these are both dynamic processes it is also important to break the sample to be tested into a number of size fractions to ensure that the results obtained are related to mineral gravity separation potential rather than a function of particle settling diameter. An example of a coarse gravity characterisation testing program utilising the Viking Cone, Dense Medium Cyclone and tabling can be seen in Figure 7.

A pilot Dense Medium Cyclone test plant consists of a mixing tank, pump, mixing box, feeder, drain panels, washing screens, and a magnetic separator. Size ranges for ore sample testing usually falls between the range of -6 mm to 3 mm. The testing sample is kept agitated in a mixing tank, and is pumped to a mixing box where the sample is introduced into a magnetic separator for concentrating. The medium is then diluted as required and the sample run again to generate sufficient data for the yield recovery curve. The Viking Cone is used to separate and characterise coarse particles (typically >6 mm) to assess their gravity separation potential. The method uses a mixture of water and ferro-silicon to maintain a slurry specific gravity. The slurry medium in the cone is pumped up a vertical shaft, and into a ‘sinks’ basket. The medium then overflows and re-circulates back down into the cone. Tracers of a known SG are used to set up the Viking cone during the test to a relative specific gravity. Adjustments to the cut point are made by changing the ratio of water to ferro-silicon. Figure 8 shows the Gekko Viking Cone test rig. Runs are done with the sample being tested over either increasing or decreasing medium specific gravity to give yield recovery data. It should be noted that the Viking Cone does have a testing limit specific gravity cut of approximately 3.8.

For material less than 1 mm the continuous gravity recovery (CGR) test should be utilised to generate a yield-recovery curve to assess the potential for gravity recovery of the minerals examined. A detailed description of this test can be found in Dominy et al (2011) and it is also discussed by Hughes et al (2010) for its role in assessment of ore suitability of the Python underground processing plant. This test is slightly different to the characterisation tests described above as it includes both comminution and gravity stages to assess the potential for gravity recovery of the ore in a comminution circuit. This methodology can be also applied to the testing procedures described above, however, this would most likely require a large sample due to the rock size involved thus would only be conducted after the initial characterisation work has shown some coarse gravity separation potential.

Once it has been identified that an ore is suitable to gravity preconcentration then further technology specific testing can be conducted to give confidence in the separation ability of the selected processing route. For example Gekko Systems utilises a pilot (1 t/h) scale IPJ to sample of material between 0.1 - 5 mm.
Coarse Gravity Investigation Tests

- ~300 kg Sub- Sample
- p100 of 6.7 mm, using VSI
- p100 of 3.35 mm, using VSI
- Sub- Sample
- Reserve Sample

Size 50 kg

- -11.2 mm +4.7 mm, +6.7 mm +1.18 mm and -1.18 mm

Dense Media Cyclone
- -8.7 mm +1.18 mm

Willey Table
- -1.18 mm

4 Concentrates

Tail

FIG 7 - Coarse gravity scoping test work flow sheet.

FIG 8 - Gekko Viking Cone test rig for gravity characterisation of coarse (>6 mm) particles.
CONCLUSION
Underground preconcentration in the context of a narrow-vein mine has the ability to make a significant impact on a project’s economics. It is thus important that metallurgical testing is undertaken on the ore in the initial stages of a project to see if the orebody is amenable to coarse preconcentration. Technology such as ore sorting and gravity concentration via the IPJ are ideal for the underground preconcentration application as they can concentrate the ore at a coarse size, they require little auxiliary infrastructure and they are easily modularised for underground installation. Successful development and long term operation of an underground preconcentration plant will rely on a high level of interdisciplinary cooperation between mining, metallurgical and geological professionals.

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REFERENCES


