

Coarse beneficiation: exploiting a natural phenomenon

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Preferential grade-by-size deportment is the tendency for metal content to increase in the fines fraction of mill feed. That is, following blasting and primary crushing the fine particles will be much higher in grade than the coarse particles.

This characteristic is important to identify for each recognised ore type as coarse particles consume a higher proportion of energy in crushing and grinding. Eliminating the coarse fraction would lead to higher mill throughput – particularly for semi-autogenous grinding (SAG) mills. In fact, the coarse pebbles or scats exiting a SAG mill are an indication of this discrepancy in energy requirements. The question is: why are the pebbles returned to the SAG mill if they've proven themselves to be more competent?

SRK is working with clients to assess whether coarse beneficiation or pebble rejection is an opportunity to not only increase mill feed grade but increase throughput – using the existing grinding circuit. Coarse beneficiation can be assessed at both the drillcore stage (even on drill cuttings) as well as during operation.

In the case of gold operations, the lower grade, coarse material is often more suitable for lower cost processing methods like heap leaching.

...continued

Coarse beneficiation: *(continued)*

Consider the diagram below which plots the cumulative metal content versus the cumulative mass of material, with increasing size.

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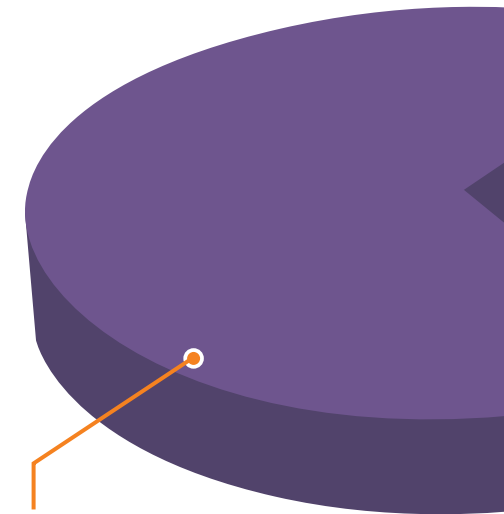
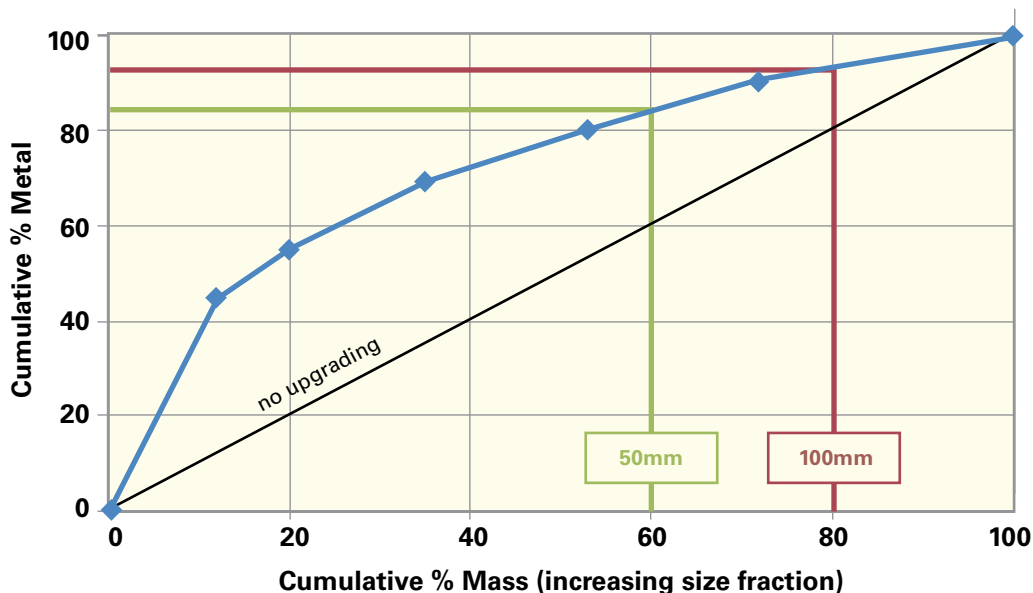
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had the same metal content, then no upgrading line would occur. For the ore type shown in blue, 85% of the metal is contained in 60% of the mass (up to 50mm) and 94% of the metal is contained in 80% of the mass (up to 100mm). Therefore, screening at 100mm would eliminate the coarse, competent component of the feed but retain 94% of the metal. For example, if the mill feed grade was 1.0g/t gold, then the finer, easier to process material would be upgraded to 1.18g/t gold. (Screening at 50mm would upgrade the feed to 1.42g/t gold.)

As an alternative to investing capital into plant expansions – why not consider generating more metal per day at the same plant capacity? Ultimately, metal per day (i.e. revenue) and not throughput or recovery is the real measure of processing plant performance.

As shown in the example, coarse beneficiation offers an opportunity to significantly upgrade mill feed – which can be used to increase revenue or lower the cut-off grade. For projects facing long haulage distances from remote deposits, it can turn such a potentially marginal project into an economic one.

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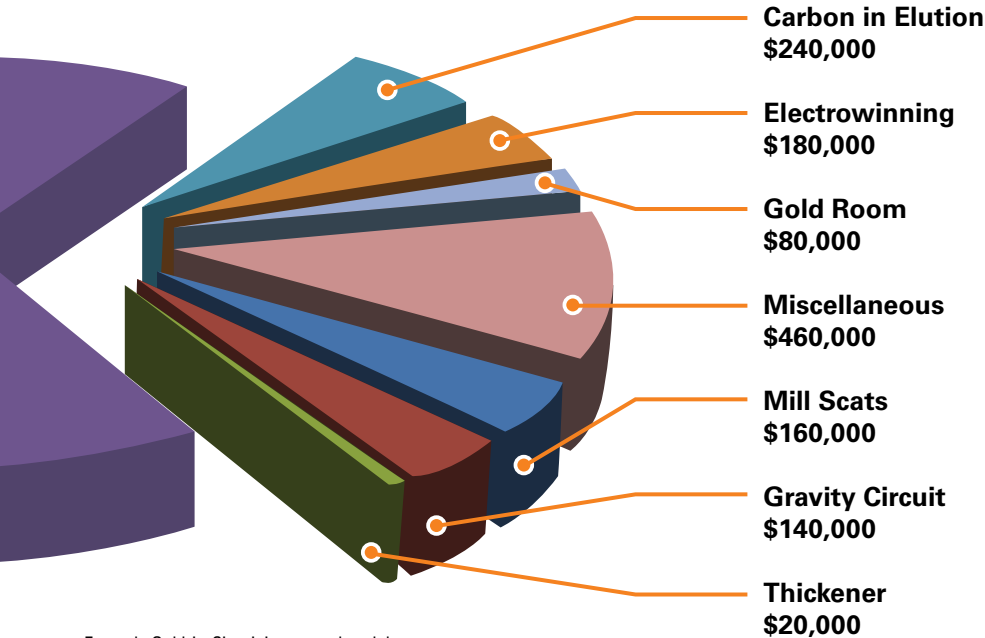
CIL Circuit, \$2,770,000

It is routine in a processing plant to sample the feed, tailings and product streams in order to make a metallurgical balance – to account for the metal processed and where it ended up. For gold plants, measuring and estimating the amount of “gold-in-circuit” (GIC) or gold inventory is also important. It represents a valuable asset and has to be evaluated regularly to ensure that all of the gold is accounted for.

Graphically represented right, the GIC can change over time depending on how much of the metal in the feed is removed as product or in tailings. If the GIC inventory measured cannot account for all of the metal, then it needs to be investigated.

Gold-in-Circuit inventory measurement

Gold Inventory in dollars



Example Gold-in-Circuit inventory breakdown

The main components of the GIC are shown in the figure above.

Significant imbalances in the GIC inventory suggest problems with the metallurgical balance method. Perhaps the main feed weightometer is not calibrated properly or the measurement/sampling methodology of inventory components is not correct or gold is being lost by theft.

Sometimes, the amount of gold accounted for in the GIC inventory is less than what is calculated from the

starting GIC plus the estimated metal in the feed: how can this happen?

In the figure above, a typical monthly GIC report shows that this plant had 99kg of gold in inventory – this represents about \$4 million in locked-up value. Of this total, most of it was in the leach tanks; however, 11% or \$460,000 in gold was associated with “miscellaneous”: caught up behind mill liners, in spillage sumps and various items of equipment. Careful steps are taken to minimise this miscellaneous gold lock-up, which is often considered

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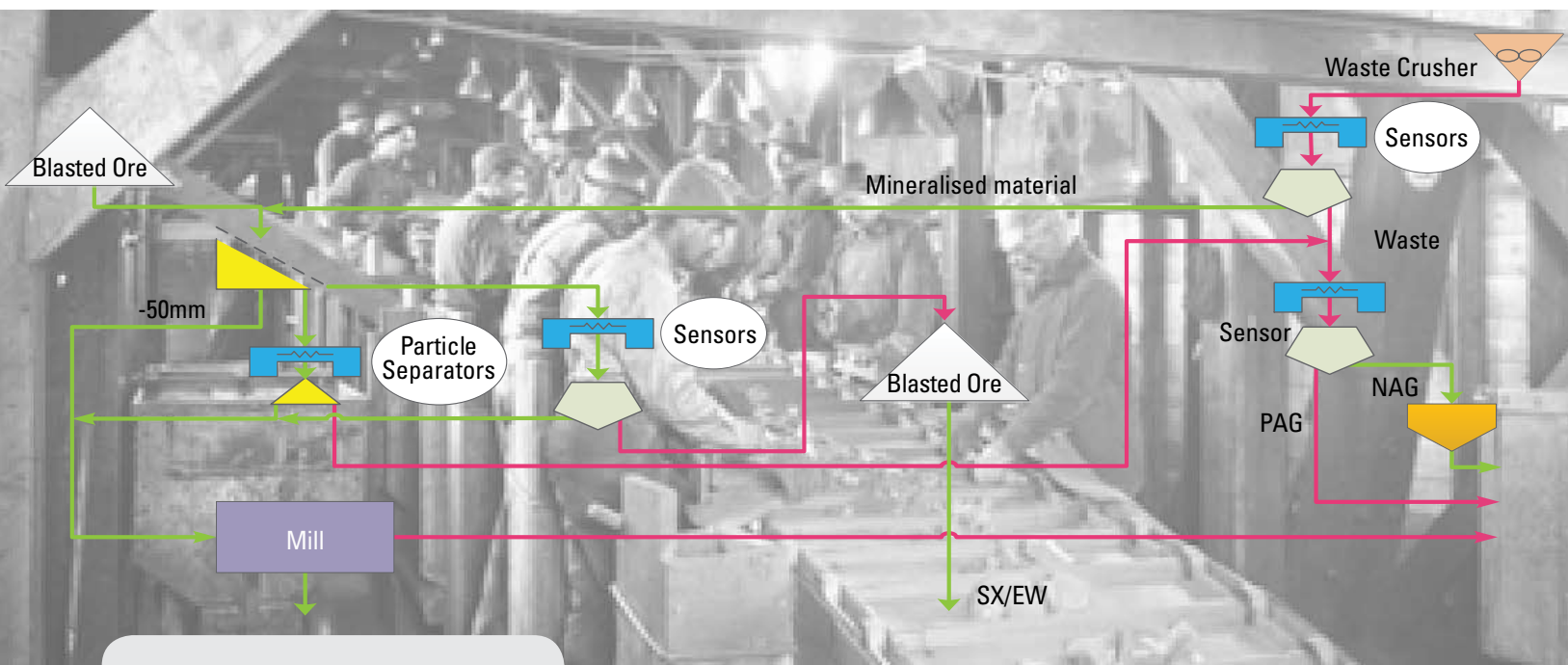
a high risk area for theft. In some cases, where practical, these high risk areas will result in some form of modification to equipment or security systems.

At the end of the accounting period, the plant operations team will make a concerted effort to minimise the inventory by converting as much of the GIC into doré in the gold room so that it can be reported as final product.

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Improving mill feed: a miner's perspective



BOB MCCARTHY

Bob is a professional mining engineer with over 30 years' experience in mine operations, mine planning, asset management, technology development and implementation, and consulting. He has worked at numerous mines, across different departments, in a variety of technical and management roles. Bob's technical strengths are in project evaluation, mine planning, mine site and project reviews (audits), and technology implementation. He is particularly specialised in In-Pit Crushing and Conveying evaluations as well as assessments for the application of pre-concentration using various approaches.

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Over the decades, with decreasing ore deposit grades, miners have turned to economies of scale and bulk mining to gain advantage. This has resulted in an inherent dilution of feed to the mill. However, a point is being reached for most ore deposits where the mill feed grades for the selective mining unit (SMU) sizes are too low to be deemed economic. So what can we do to improve mill feed?

Mineral processors have long had to consider "mineral liberation". The smaller the grain size, the more likely a particle will contain pure or near pure mineral, which can then be separated and retrieved by various methods. However, what now needs to be considered by both mineral processors and miners is "waste liberation". At what size does a particle have insufficient mineralisation to exceed the cut-off grade and can no longer be deemed "ore"?

Ore deposits are found in many forms; they can be vein hosted hydrothermal deposits, with short-range spatial variation in grade, or porphyry deposits, which are more disseminated and smoothed in grade. Another way of considering a deposit's disposition of grade is to refer to its heterogeneity. Heterogeneity is the degree to which waste and mineralised material are distinguished in a deposit. SRK has developed methods to assess the heterogeneity of deposits which can then be exploited to determine how waste can be liberated.

However, knowing deposit heterogeneity is only part of an assessment for improving mill feed. It is also important to have an understanding of the relative hardness of mineralised and gangue material, as well as the deportment of mineralised material to the coarser or finer size fraction in the mill feed.

Metallurgical challenges or opportunities

Miners can play a role in improving mill feed. Armed with knowledge of the deposit heterogeneity, material hardness, and mineral deportment, certain processes and technology can be introduced ahead of the mill to remove waste from the feed or to segregate the mill feed into different streams for alternate processing methods.

Methods being investigated and developed by SRK include:

- SMU size definition – refine the SMU size to maximise opportunities to segregate waste from ore at that scale;
- Differential blasting of ore – target zones of gangue and mineralisation in an ore block to exploit differences in hardness and mineral deportment, and thereby create coarser waste particles;
- Screening of mill feed – exploit mineral deportment to create different ore streams at different size fractions or to allow outright rejection of waste. This can be done on blasted ore or after crushing;
- In-pit crushing and conveying (IPCC) – though regarded as a means to reduce haul trucks, it also presents opportunities to segregate conveyed material through mineral sensing and sorting; and
- Mineral sensing and sorting – exploit certain characteristics of conveyed material to identify opportunities for bulk or particle sorting. Such sorting can operate in pre-concentration (waste rejection) or scavenger (mineral retrieval) mode

Stay tuned for more details on these topics.

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In conducting technical due diligences, SRK's recent experience has found the majority of projects to be "metallurgically-challenged". This is often due to low grade or complex mineralogy or at times, ore hardness; sometimes it is a matter of inadequate power, water or tailings handling.

Problems arise when the selected flowsheet is not appropriate for the range of ore properties – a "one size does not fit all" situation. Very often, companies do not appreciate or acknowledge the potential for variations in metallurgical performance, expecting the operations team to make the best of it.

How often does a company truly understand their ore variability – both now and in the future? Can they predict (to a reasonable level of accuracy) the expected changes in performance and have a plan in place to mitigate them? This may not be the case as confidence in these predictions is low and therefore, can be ignored.

Of course, the common term for this is geometallurgy – but does this include the potential for changes in the process flowsheet? In the figure below, a typical 16-year mine plan shows six metallurgical domains.

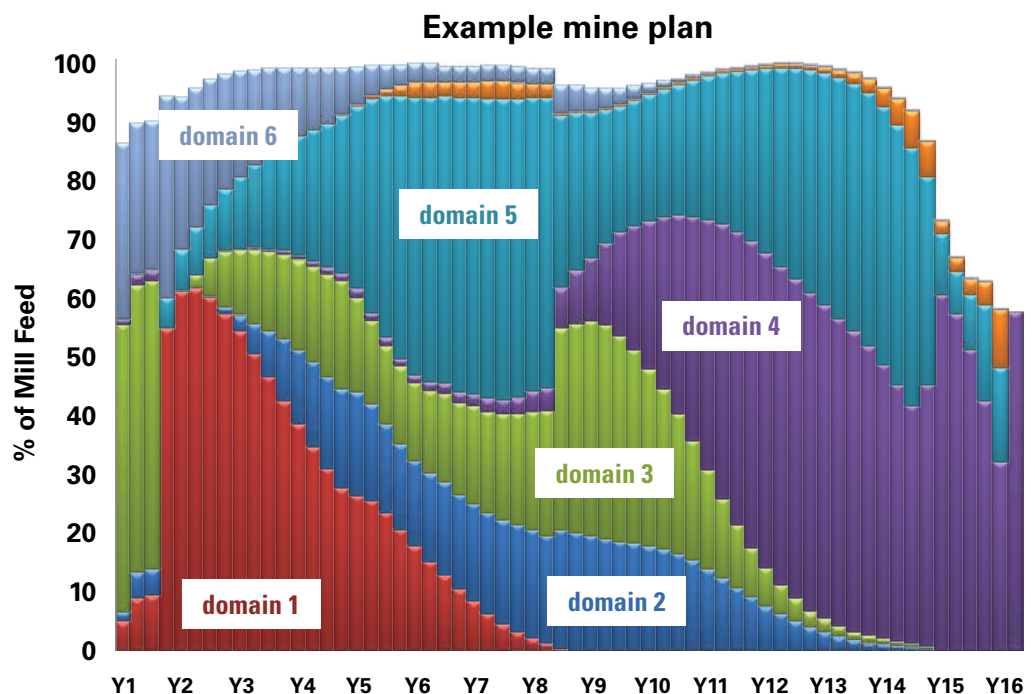
How were these domains derived and are they metallurgically-relevant? What will happen in the middle of the mine life when Domain 4 arrives at the mill? Does it justify a change in process flowsheet or an expectation that problems will be dealt with at that time?

SRK is assisting clients stuck with a fixed flowsheet and anticipating variable feed conditions: can feed quality be improved (e.g. blast fragmentation) or can the principles of Grade Engineering® be applied? That is, by blending/sorting ahead of the process plant or methods of pre-concentration, including coarse beneficiation.

SRK is advocating flexible process flowsheet design including "staged reduction in size and progressive upgrade" – recovery of product at every opportunity and removal of waste at every stage.

Remember: all ore is not created equal and equal grade does not mean equivalent performance. One thing is for certain – with an inflexible flowsheet, your metal recovery will not remain constant for the life of mine.

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Grinding circuit improvements at Gold Fields Granny Smith operation

The Gold Fields Granny Smith mine in Western Australia has a long history of collecting high quality, grinding survey data from which to make circuit improvements. This started when the semi-autogenous grinding (SAG) mill was originally operating at the Placer Dome Kidston mine, after being relocated to Granny Smith for Barrick Gold and continuing now under Gold Fields Australia ownership.

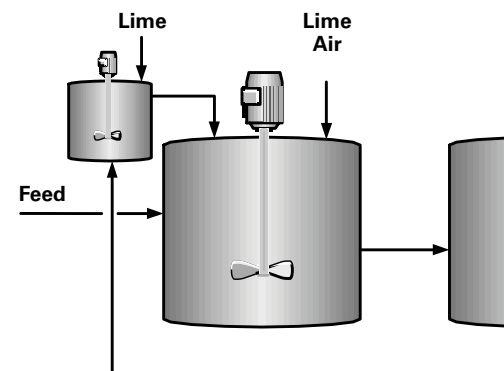
With the assistance of SRK, Granny Smith achieved incremental crushing and grinding circuit improvements based on frequent survey data as well as stabilising/optimising control methods. They have operated their circuit under a wide variety of configurations, tonnages and feed sizes over the past eight years and met expectations when benchmarked against theoretical specific energy estimates.

To date, they can directly attribute an increase in gold recovery to these grinding circuit changes, while having to operate within a limitation on the cyclone overflow % solids (due to a

lack of pre-leach thickening). One of the reasons for their circuit stability is the very fine secondary crushed product size they are sending to their grinding circuit. This allowed them to reduce the SAG mill media size and operate at a slower speed without the rock load building and destabilising the mill. In turn, this provided spare mill capacity which can be used to assist the ball mill. One of SRK's recommendations under consideration is returning a portion of the cyclone underflow back to the SAG mill. The spare mill capacity can then be applied to the material without the need for dilution water – and maintaining the required leach feed % solids.

After each stage of optimisation, SRK conducted full surveys of the grinding circuit to confirm the improvements and to benchmark current operational efficiency against historical performance. It is safe to say that the Granny Smith comminution circuit has a well-documented history with further plans for improvements in the future.

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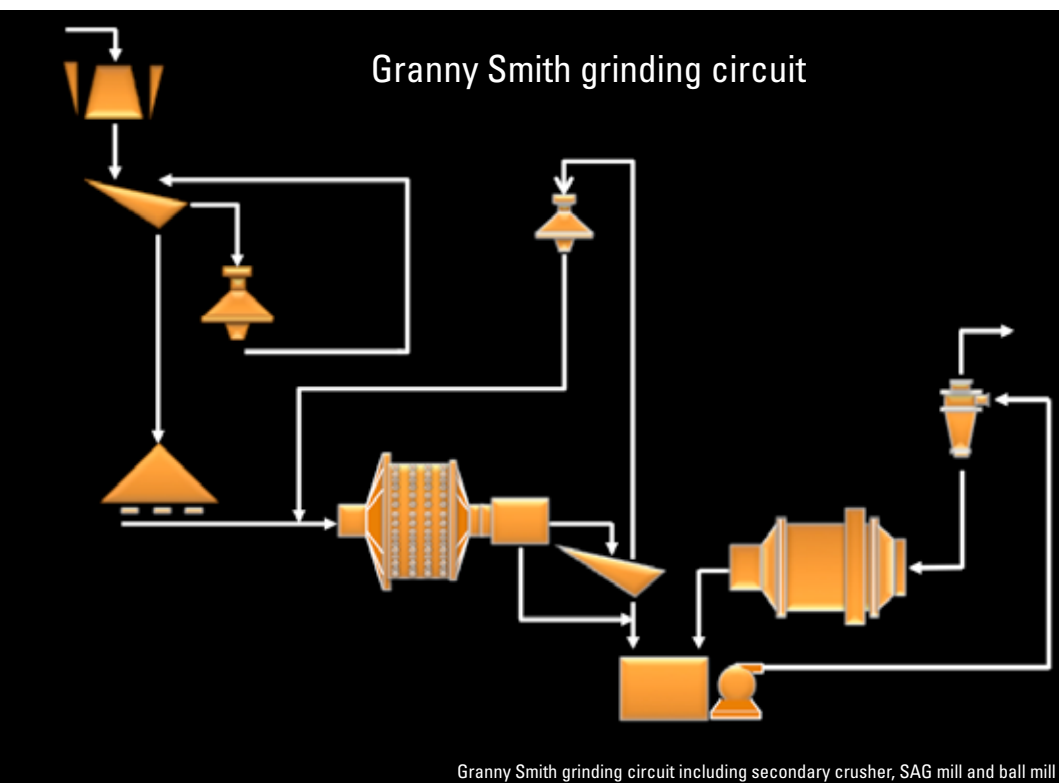


Take a look at the flowsheet above.

Can you tell if this is a step in the process plant or a water treatment plant? Mining operations are building dedicated water treatment plants costing between 10s and 100s of millions of dollars, when it is possible that these are wasted expenses if the complete process is considered.

Mineral processing plants are generally designed to achieve the highest recovery of valuable material, with limited regard for the cost of managing waste products—both solid and water components. The highest recovery processing route can, in fact, lead to costly issues downstream, which can include water treatment. In addition, handling storage of mine waste to eliminate environmental impacts from acid rock drainage and neutral pH contaminant leaching. This is particularly true considering the significant mine closure costs that can remain in perpetuity.

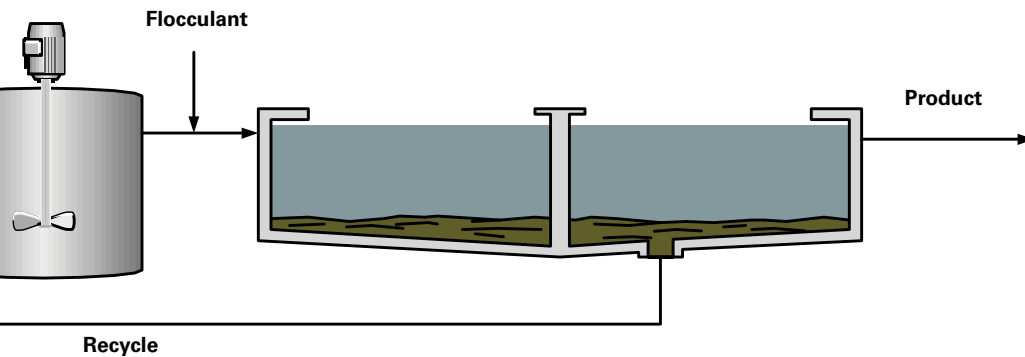
Often the design and selection of metallurgical and waste management engineering solutions take place



Granny Smith grinding circuit including secondary crusher, SAG mill and ball mill

Unlocking potential water quality improvements in the process mill

Do these stages belong in the process plant or water treatment plant?



in technical 'silos' and do not consider synergistic opportunities. However, by having geochemists, water management engineers and metallurgists work together, there exists potential for improved project economics and reduced environmental risk without the need to design and build dedicated water treatment plants and, instead, use the processes in the mill to manage water quality.

Typical mineral processing steps, such as grinding and lime addition, provide the potential to either remove contaminant metals through surface sorption (i.e. higher surface area from ground ore) or contaminant co-precipitation from lime addition. These mill processes are the same strategies used in water treatment plants and, given the high throughput of most processing plants, reclaim water volumes are also high and the ability to 'treat' significant volumes of water is possible.

To ensure that discharge water meets receiving water quality guidelines, two recent examples of using in-plant water treatment, as opposed to dedicated

water treatment plants, include the Kitsault project in northern British Columbia, Canada, and the Sisson project in central New Brunswick, Canada.

At Kitsault, cadmium sorption in tailings slurry was demonstrated. The Sisson project is using lime to clarify water for the process plant, but it also demonstrated that arsenic co-precipitation after lime addition in the mill could off-set the need to construct a dedicated arsenic water treatment plant.

While not every mining project may have the potential to realise these benefits, the number of potential opportunities is likely extensive, given how rarely environmental and metallurgical teams collaborate. For a small amount of investment, significant gains could be realised.

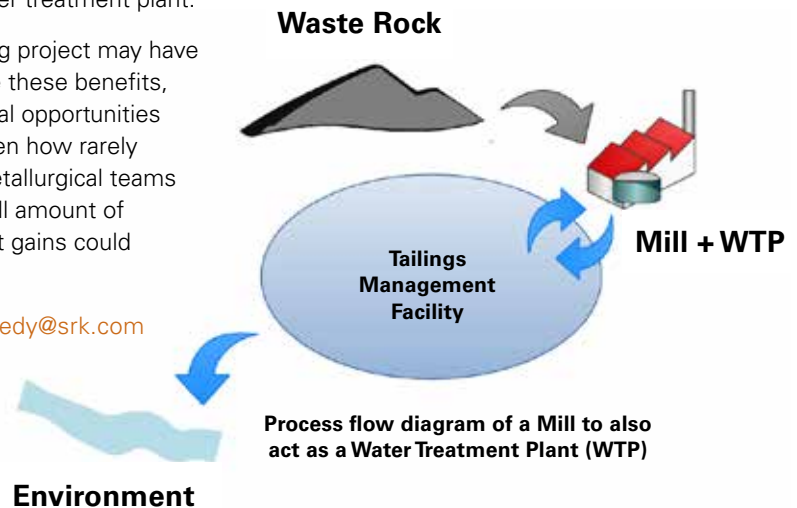
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CHRIS KENNEDY

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Process flow diagram of a Mill to also act as a Water Treatment Plant (WTP)

Lithium extraction: a question of being in the right neighbourhood

ROB BOWELL

Rob is SRK's Corporate Consultant in Geochemistry & Geometallurgy (PhD) with internationally recognised expertise in the geometallurgy of complex ores. He spent over 28 years specialising in applying geochemistry and mineralogy to diverse mining and engineering projects, including characterising oxide ores amenable to in situ recovery (ISR), solution mining and heap leaching, refractory gold ores, autoclave mill residues, complex base metal and uranium ores and Rare Earth Element mineralogy. Rob has worked on ISR projects for copper, uranium, lithium recovery from brines, mine waters and ISR fluids and potash solution mining on nearly every continent.

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Lithium-rich brine source, South America

One of the few positive commodities in 2015 was lithium. Improvements in the performance and durability of lithium powered batteries have made electric cars a reality. The search for suitable raw materials has galvanised many junior mining companies to switch from uranium, gold, nickel or copper to searching for lithium.

Lithium is the lightest metal in the periodic table and the lightest solid. Its chemistry is similar to sodium and displays an aggressive reaction with water. This reactive chemistry and light weight reflect the fact that lithium has only one layer (or shell) of electrons around the atom's core thus, it has virtually no insulation (or loss of conductivity) as other elements. This makes it an ideal battery component. Lithium batteries are lighter, smaller, provide more power than lead, copper, vanadium or nickel-zinc alloys, and they last longer. Lithium is relatively abundant in nature. It occurs mainly in silicate minerals in hard rocks often as a trace component, or it occurs as a chloride

salt in brines and evaporates when associated with volcanically active areas. Lithium can be extracted from its mineral hosts by: water soluble extraction from salts; and acid leaching from resistant silicate minerals.

Obviously, the brine-associated lithium is easier to extract from lithium bearing salts. However, magnesium and chloride are also extracted. For use in batteries, lithium carbonate requires several steps of concentration, separating the salt components, purifying the lithium to remove impurities and carbonation to produce a useable high-purity lithium carbonate product. When processing calcium, sodium, potassium and particularly magnesium must be separated for product purity.

Broadly, two styles of hard rock lithium exist, pegmatite and volcanic-associated rocks. Lithium occurs in pegmatites often as attractive, collectable crystals showing a wide range of colour from white through pink to a purple and even forming gemstones such as kunzite.

Vanadium-uranium separation: or is it just good chemistry?

In cooking, some ingredients have such an inherently strong taste that a few grains can be detected on even the most insensitive of palates. Chili peppers are a good example and whereas in a stew they can provide a balanced taste, in a sweet cake the taste is less than desirable. So it is with some chemical elements; for example, uranium.

Typically, uranium occurs along with similar elements as a function of geological and geochemical processes. For the metallurgist this can present challenges when looking to isolate and generate uranium compounds and products or isolate associated elements. Even a few parts per million of uranium can result in a product being considered “contaminated” or radioactive.

In defining a new source of battery-quality vanadium, American Vanadium involved SRK to advise on the chemistry

and separation of uranium from vanadium and in producing high-purity vanadium polyelectrolyte for use in vanadium batteries. Working as part of the owners’ team, SRK was involved in the design and interpretation of testwork and helped develop a suitable flowsheet to promote vanadium extraction and separate uranium that was leached along with the vanadium. Working with chemical reagent suppliers, a novel flowsheet was developed that will allow the company to produce a suitable quality vanadium product to sell into the battery industry and a uranium by-product that can also be sold. Applying good chemical knowledge and experience in process engineering, SRK assisted the client in achieving their goals.

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Extraction begins with physically separating the ore-bearing minerals through crushing and milling.

Once separated, the lithium minerals require destabilisation at high temperatures with an aggressive leaching agent, such as sulfuric acid. The lithium sulfate produced is segregated from the acid by ion exchange or solvent extraction before finally being neutralised and exposed to air and carbon dioxide to form lithium carbonate. As with brines, other constituents such as magnesium and chloride are removed to avoid contaminating the product.

Selecting a suitable process for lithium requires good understanding of the geological occurrence of the element and its neighbours. Some, like tin and tantalum, can be valuable by-products; others, such as magnesium, are undesirable neighbours that need to be separated to avoid contamination.

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Vanadinite Pb-Cl-vanadate mineral, also an ore of vanadium, Atlas project, Morocco

Iron ore beneficiation testwork

Iron ores come in many shapes and sizes (and mineralogies), so there is no one size fits all approach to beneficiation.

For magnetite ores, it is typically necessary to liberate the individual magnetite grains from the host rocks, after which beneficiation is relatively straightforward due to the magnetic properties of magnetite. However, flotation may be required as a final stage to remove residual silica, phosphorous and/or sulphide minerals following magnetic separation.

However, for other iron ore types, full liberation of the iron minerals may not be required. Direct Shipping Ores, as the name suggests, require no beneficiation, although frequently wet screening is required, (particularly for tropical deposits), to minimise adhesion of fines to a potential Lump product. Removal of slimes can also be desirable both from a product quality perspective (less for iron upgrading than for aluminum reduction), and to reduce the material's Transportable Moisture Limit. The other key aspect to test is whether a potential Lump product has sufficient mechanical strength to remain as Lump from mine site through to market.

Note that it is the material in between these two iron ore type end members that can prove the most problematic.

In a West African context this material is typically called Saprolite; in the Brazilian context this is Itabirite, and the Brazilian industry has very successfully developed flowsheets for this material using combinations of gravity separation, magnetic separation and flotation. For the most part they have exploited friable itabirite – material that requires little if any grinding; while compact itabirites have been less frequently exploited as they require grinding at a higher process cost.

For West African type deposits, SRK's experience is that there is no guarantee of successfully developing a viable flowsheet. Ores can often respond to gravity and/or magnetic separation. However, due to the presence of lower-iron content, iron minerals such as goethite, mass yields and recoveries to high grade concentrates can be low. Trade-offs are then required between recovery and product quality (iron grade and penalty element content).

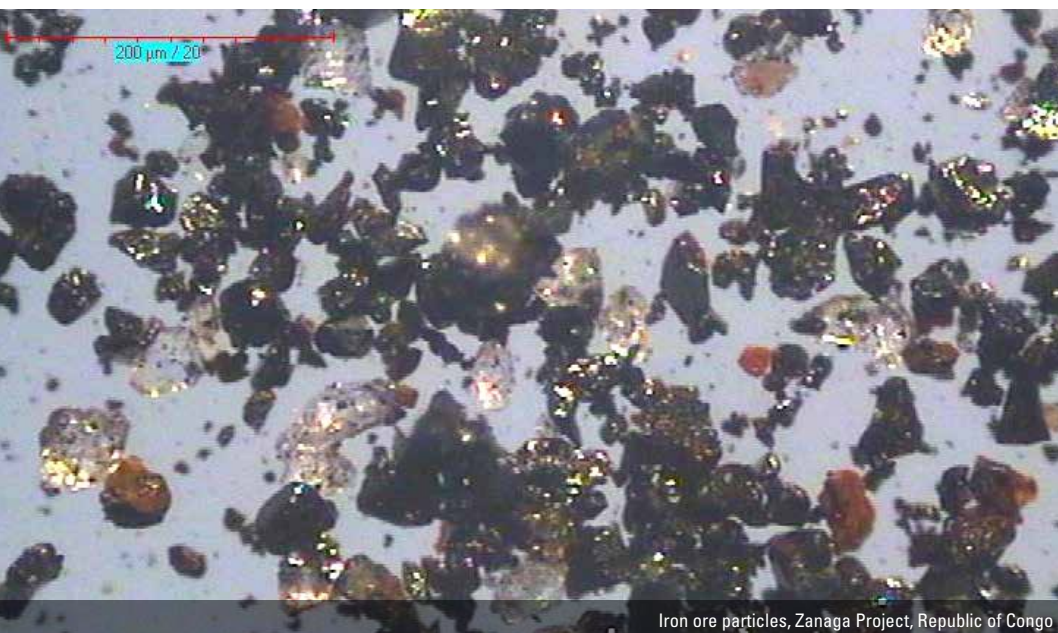
As with any metallurgical flowsheet development, mineralogy is key. SRK has looked at a deposit where the mineralogy consists of ten micron plates of hematite cemented by quartz, proving an insurmountable challenge for both liberation and separation, and a disappointing outcome for the client!

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The AMIRA “Metal Accounting Code of Practice and Guidelines” (2007) has established best practice in process plant metal accounting. The code is based on the “check in, check out” concept; sampling the mass flow of the commodity of interest (e.g. gold) as it crosses a Transfer of Custody boundary, such as the feed of a plant and the different product points of the plant (including tailings). Measuring the mass flow of the commodity requires measuring the stream flow and collecting an assay of the stream via a sample.

Classic sampling theory defines seven sampling errors. These range from errors fundamental to the material being sampled (e.g. bulk particle size, grain size of the mineral of interest), to those relating to how the material is presented to be sampled (variations in time and space) to those relating to how the sample is taken (how the sample cut is defined and removed).



Iron ore particles, Zanaga Project, Republic of Congo

Pitfalls of sampling



Plant sampling installations

The fundamental error is related to the weight of the sample that needs to be taken. This weight increases with increasing crush size and with decreasing grade, but decreases with increasing liberation of the mineral of interest. This error becomes particularly problematic when sampling a coarse feed in a gold plant (such as to a SAG mill). While there are some sampling devices on the market, which can take a good representative sample of ore on a conveyor, the weight of sample required to arrive at an acceptable error often makes us question the merit of taking such a sample – a sample of a manageable size is likely to produce an assay with a large degree of uncertainty associated with it.

With the trend of plants being built by engineering companies coming from a petrochemical background, we find numerous examples of samplers, especially pipe samplers, which are probably perfectly suited to sampling a well-mixed liquid stream, but which

are entirely inappropriate for sampling a slurry. The best method for sampling a slurry is still to use a cutter cutting across a falling stream.

Other pitfalls include not taking time lags into account, such as taking a sample ahead of a thickener to represent the feed to the subsequent process.

Despite the check in, check out philosophy of the code, it states that in cases such as gold and base metal plants, the recommended strategy is to reconcile based on: tailings, feedrate and production (gold) or feed, concentrate and tailings assays (base metals). While this approach can be somewhat clumsy in a gold plant with a significant gravity-recovered component, the focus should be on taking samples of high quality rather than generating poor quality data.

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Reference: AMIRA P754, 2007. Metal Accounting Code of Practice and Guidelines: Release 3 AMIRA International, February 2007.

JOHN WILLIS

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of metallurgical testwork, flowsheet development, comminution circuit modelling and simulation, plant auditing, due diligence and feasibility studies and plant design. John joined SRK in early 2008, and works in commodity areas, including gold, copper, molybdenum, iron ore, phosphate and potash.

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Leveraging your rock mass characterisation



Several in-field empirical, field-based and laboratory methods are used to determine intact strength: for example, point-load, unconfined

compressive and triaxial strength testing. The 'toughness' of the intact rock is related to the grain-size, shape, and bond-strength between grains. These strength measures are related to (but do not necessarily correlate with) work-indices used to quantify energy expenditure using different types of milling methods.

On a larger scale, joints separate individual rock blocks. The joints form a pre-existing network of discontinuities, which affect the gravity and confinement-driven strength of the material.

ANTON BLOEM

Anton is a Senior Consultant on Rock Mechanics (BSc) who has more than twenty years of mining-industry experience in rock mass characterisation aimed primarily at mine design. This experience is geared towards open-pit slope design and implementation. Anton's current interests and work include primary data collection methods, rock mass damage and dilation, *in situ* parameter estimation, parameter verification using down-hole geophysical tools, geotechnical model development, and operational open-pit slope modelling and design adjustments.



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Mining involves extracting a desired commodity, like gold, from a rock mass – in which the volume of waste significantly exceeds that of the mill feed. Within the mill feed, there are some fractions that are more desirable than others (e.g. low intact strength, small fragment size, and/or low-clay composition). The less time, energy, and cost it takes to mine, move, and process the ore to release the desired minerals, the more profitable the operation will be. An industry-proven way to decide how the rock is handled, is to know and understand the physico-mechanical properties of the rock mass within the mine and where the ore is drawn – this is called rock mass characterisation.

Within the *in situ* rock mass there are two main components to be considered: the intact rock, and the discontinuities that separate the individual rock blocks. Intact rock strength is a measure of the 'hardness' of the material.



Rock mass strength domains for an open-pit

Hydrogeochemical mining

The two extremes of the joint-network phenomenon can be thought of as the rock mass that is observed in an intensely altered porphyry-style deposit, with intact weak rock-blocks of less than 0.1m³ compared to the widely spaced joints seen in marble dimension-stone operations, in which block sizes of 100m³ or more are not uncommon.

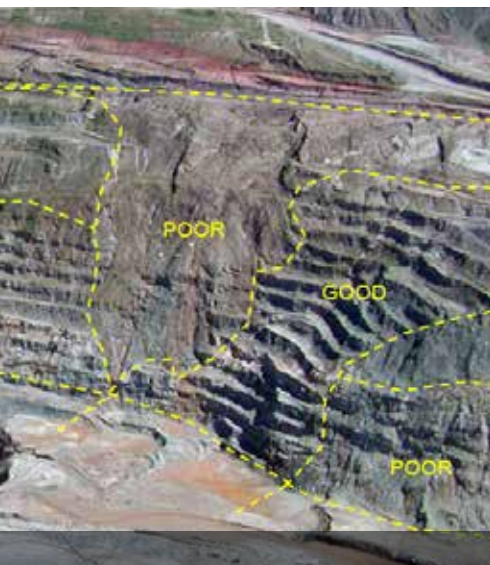
The spacing, orientation, and properties of the 'sets' of joints affect the direction of blast-energy effectiveness (and the stability of the final excavation). Within that fabric, faults form macro-scale planes of structural weakness, which affect the mine design and influence the hydraulic conductivity of the rock mass.



Leveraging the available knowledge of the rock mass, in the form of the domain models built using robust

quantification methods, assists with planning and scheduling to minimise the energy expenditure and maximise the realised dollar-value of the rock and ore being processed. This is an iterative process, one which should be refined at each level of study (scoping, PFS, FS, and into production), and which ultimately leads to a bench or face-scale characterisation of the rock properties within the mine.

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When water contacts a solid, a portion of the solid can be dispersed or even dissolved within the water (depending on the chemistry and solid form). This reaction has challenged many miners over the centuries and, back in 1558, Georgius Agricola commented on "poisonous waters that spew from mines".

Although this environmental risk can present a serious challenge to mining projects, in other places the passive release of metals or mineral components from an ore or mineral formation can present an opportunity for cost-effective mining. Managing and even enhancing the dissolution of soluble components that have value can present an economic means to process ore deposits that may not be economic by conventional mining. This could reflect stringent environmental controls, depth of the mineral deposit or perhaps low grade. Mining by injection can be divided into two forms:

One form is solution mining by which water-soluble minerals, usually using one or more drilled wells to dissolve the minerals with water in a congruent dissolution process

The other form is in-situ leaching (also called in-situ recovery or ISR) a mining process used to recover minerals such as

copper and uranium through boreholes drilled into a deposit, into which weak solutions of chemical reagents such as sulfuric acid, ammonia or sodium carbonate are pumped to preferentially extract metals

As attractive as such processes sound they do have drawbacks. The hydrogeological and geochemistry of the leached formation needs to be adequately understood to ensure leaching solutions can be managed and do not migrate into the environment uncontrolled. Complex hydrogeochemical reactions at the leaching front cannot be easily controlled, unlike in a process plant or even heap leach, and these need to be predicted prior to operations and monitored to maximise efficiency during the life of mine.

SRK has considerable experience in hydrogeochemical mining of salt, potash, boron, uranium and copper. SRK has completed hydrogeological and geochemical characterisation and prediction studies as a basis for well field design and operation. We have undertaken infrastructure and financial assessment of such operations, as well as environmental baseline and clean-up post-mining studies.

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Solution mining well, Africa

Incorporating geometallurgy into strategic mine planning

The objective of strategic mine planning is to maximise the near-term cash flow of a mining project. A mine operator needs to maximise the discounted cash flow and net present value to help secure low cost financing for mine construction. The operator selects a mining direction and a pit phasing strategy.

Conventionally, the value of each block of ore is calculated from the metal grade, recovery and processing costs and that value drives the strategic mine planning process. Processing costs are estimated on a per tonne basis and combined with the estimated mineral revenue to determine a value per tonne. The areas with the highest value on a per tonne basis are deemed the most desirable to mine first.

However, this process does not account for the fact that not all rock types, alteration zones or mining areas necessarily have the same hardness and grind at the same rate. This mine planning strategy can be improved by incorporating more geometallurgical modelling practices.

To maximise the revenue generated in a finite period of time, the comparative value of each ore block should be estimated on a time basis rather than a tonnage basis: the value could be calculated as cash flow per day, instead of cash flow per tonne.

Consider that a mine planner has two blocks of ore and wants to select the best

block to mine first. On a tonnage basis the first block may be worth \$100/t and the second is \$75/t. Is the first block the smart choice? Suppose that further metallurgical testing indicates that the second block will grind twice as fast as the first. Now the second block will actually generate a better cash flow.

It is not necessary to model a unique processing rate for each block for this methodology to have a positive impact on the mine plan. Simply identifying broader zones of harder or softer ore, be it alteration zones, rock types or mining areas, can materially improve a mine plan.

In addition to strategic mine planning, this same philosophy can be applied to pit optimisation. Many processing costs and general and administrative costs are fixed on a time basis. When we acknowledge that the plant will process more tonnes of one rock type in a day than another, we can see that the effective processing costs will differ. Applying a time based block value in pit optimisation results in an ultimate pit shell which accounts for the higher real cost of hard zones.

Incorporating geometallurgy into strategic mine planning creates the opportunity to exploit softer ores which will produce better cash flow than harder ores.

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Crushed heap leach pads of copper ore

At first glance, heap leaching can appear an extremely simple technology; however, without proper characterisation, engineering and design, heap leaching faces significant issues that can affect the overall economic viability of the project. Combined with compartmentalising the project and pressures to skip conventional steps in the normal project development process (advancing from the conceptual or scoping study phase to feasibility or final design), the overall project viability and economics can be inadvertently affected or constrained during operations.

With lessons learned from the design, construction and operation of numerous heap leach pads worldwide, SRK recommends the following for a successful heap leach facility:



Experience based approach to successful heap leach pad design



- Develop a site specific design that accounts for such conditions as metallurgy, topography, climate, geotechnics, environmental and closure conditions;
 - Develop a rigorous program for sampling and metallurgical characterisation that assesses the variability of the ore;
 - Select the appropriate heap leach pad (HLP) type, containment, and ore loading system;
 - Consider adjacent facilities and anticipate potential facility changes in the heap leach life cycle, including closure conditions;
 - Select the system for solution management (including irrigation, solution collection and water balance system), that considers upsets, such as extremely wet or dry conditions;
 - Monitor the operational kinetics against those used in the design process, update with metallurgical testing performed during operations, and
 - Perform a risk assessment at numerous stages of the design process.
- In addition to these technical recommendations, SRK suggests that the design process should:
- Benchmark with other projects;
 - Implement a peer review program;
 - Follow a staged design process that covers the entire HLP Life cycle;
 - Allow for construction and operational flexibility in the design;
 - Exceed minimum requirements and define battery limits early on; and
 - Document the process to provide transparency and allow for regular reviews of key decisions.

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TERRY MANDZIAK

Terry has over 26 years of responsibility and technical experience for mining projects, in both industry and consulting. A registered professional engineer, Terry has managed tailings and heap leach design projects, with responsibilities that included site selection, site investigation, data interpretation, laboratory analysis, slope stability assessment, costing analysis, and development of specifications and construction documents. He has also managed multi-disciplinary engineering teams on NI 43-101 compliant conceptual, pre-feasibility and feasibility studies. Terry has worked on projects throughout the world, including North America, South America, Turkey, China and Africa.



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Grant is a senior consultant specialising in mining with SRK Canada's Mining division. Prior to joining SRK, Grant worked at a number of mining operations across Canada in design, planning and supervision roles. His primary experience is mining feasibility studies and due diligence reviews with expertise in using mining specific software including MineSight 3D, Vulcan, GEMS & Whittle. Grant is currently the Chair of the CIM Vancouver Branch.



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Successful metallurgical program for the Montagne d'Or gold project



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Eric has over 30 years' experience in the minerals industry. He specialises in consulting for plant operations, process development, and project management and has extensive research & development experience with base metals, precious metals, ferrous metals and industrial minerals. Eric has been involved with numerous third-party due-diligence audits, and with preparing project conceptual, pre-feasibility and full-feasibility studies. He has also held both general management and plant superintendent positions for several gold and base metal mining operations.

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On site at Montagne d'Or gold project

During 2016, SRK undertook a feasibility-level development program to describe the metallurgical process for Nordgold's Montagne d'Or gold project located in French Guiana. The objective was to develop a practical process flowsheet and define the process operating parameters and metal recoveries in sufficient detail and to the required level of accuracy. This included developing a process design criteria, equipment requirements, process capital costs and operating costs. This program involved numerous stakeholders, professionals and organisations that all contributed to a successful outcome. The following points were instrumental in the program's success:

- Holding a kick-off meeting with all stakeholders and disciplines to ensure that the scope of the program and expected outcomes are fully defined.
- Involving experienced project geologists and mining engineers in the selection of drill core intervals from which both master composites and variability composites could be developed for the metallurgical program. For the Montagne d'Or project, three master composites were selected to represent three major ore zones. In addition, twenty-two variability composites were developed to represent different ore lithologies, grade ranges and mining phases. Also, comminution composites representing each of the ore and waste lithologies were developed from core.



- Involving the metallurgical staff from the selected process engineering firm throughout the metallurgical program. This is essential at a feasibility level of study to ensure that the program fully captures all of the processing parameters required to define the process design criteria and selected process flowsheet.
- Coordinating with geochemists and geotechnical engineers to ensure that process products were obtained during the metallurgical program for specific geochem and geotech evaluations.

The metallurgical program conducted for the Montagne d'Or project served as the basis for defining the process design criteria for a flowsheet that includes: primary crushing, SAG mill grinding, gravity concentration, carbon-in-leach cyanidation with O_2 injection, tails thickening and cyanide detoxification based on the SO_2 /Air process. An average overall gold recovery of about 94% is projected and includes allowance for losses due to inherent plant inefficiencies. It is worth noting that leach enhancement with O_2 injection resulted in reducing the required leach time from 48 hours (with air injection) to less than 30 hours.

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- Selecting qualified and experienced metallurgical laboratories to undertake the defined scope of work according to the defined schedule requirements. Several different commercial metallurgical laboratories specialising in comminution, cyanidation, gravity concentration, solid liquid separation, carbon adsorption circuit modelling and cyanide detoxification were used for the project.
- Employing close management and supervision of the metallurgical program conducted at each of the laboratories with timely data review and feedback to allow the program to move forward without delay.



Core from fresh, unaltered bedrock at Montagne d'Or

Poor gold reconciliation: acknowledge the nature of the ore

Gold reconciliation audits are often motivated by the following question:

Did the measured gold ever exist?

- If yes, locate the gold if it is still within the circuit, or identify the likely route by which it left.
- If not, establish reasons for the erroneous estimation and propose remedial measures to rectify.

In essence, gold discrepancies can be reduced to one of sampling/measurement deficiencies or physical losses/accumulations, or a combination of both. While gold theft is a real risk, this is generally not our focus.

VIC HILLS

Vic is a Mineral Processing Consultant B Eng Chem, with over 37 years' experience in the precious metals industry. His career has included nine years in middle and senior plant management, seven years as consulting metallurgist for South African gold, uranium and platinum mining companies, before embarking on an independent consulting career. In addition to base metals, precious metals and uranium, project exposure has included chrome, iron ore, manganese, industrial minerals and rare earth elements.



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Clearly, one should assess the metal accounting systems and procedures but, in certain instances, one should also acknowledge the nature of the ore.

For example, in a large South African gold mine, two shafts enjoyed the luxury of dedicated plants. Declining tonnages resulted in the decision to process ore from both shafts through the larger, more modern plant. Recovered gold was allocated between the shafts in proportion to the respective head content, with gold grade being based on coarse run-of-mine samples taken by automated cross-belt samplers. Sample size, frequency and size reduction/splitting procedures were considered to be good. Almost immediately, however, the indicated gold recovery of the smaller, lower-grade shaft dropped, bringing its viability in doubt.

Interrogating the systems and procedures could not answer the question. Importantly, it was known that the reef geology and gold deportment of the two ore sources differed (see below).

Video footage showed that the cross-belt sampler over-sampled finer material, which would tend to bias the grade of Shaft 1 Reef upwards.

The aperture of the sample cutter did not respect the basic rule of three times the maximum fragment size. This resulted in rejecting low-grade coarse particles, which further biased the value of Shaft 1 Reef upwards.

Ultimately, it was concluded that the gold had existed but as a consequence of the nature of the reef as well as the sampling methodology, recovered gold had been incorrectly allocated to the detriment of Shaft 2.

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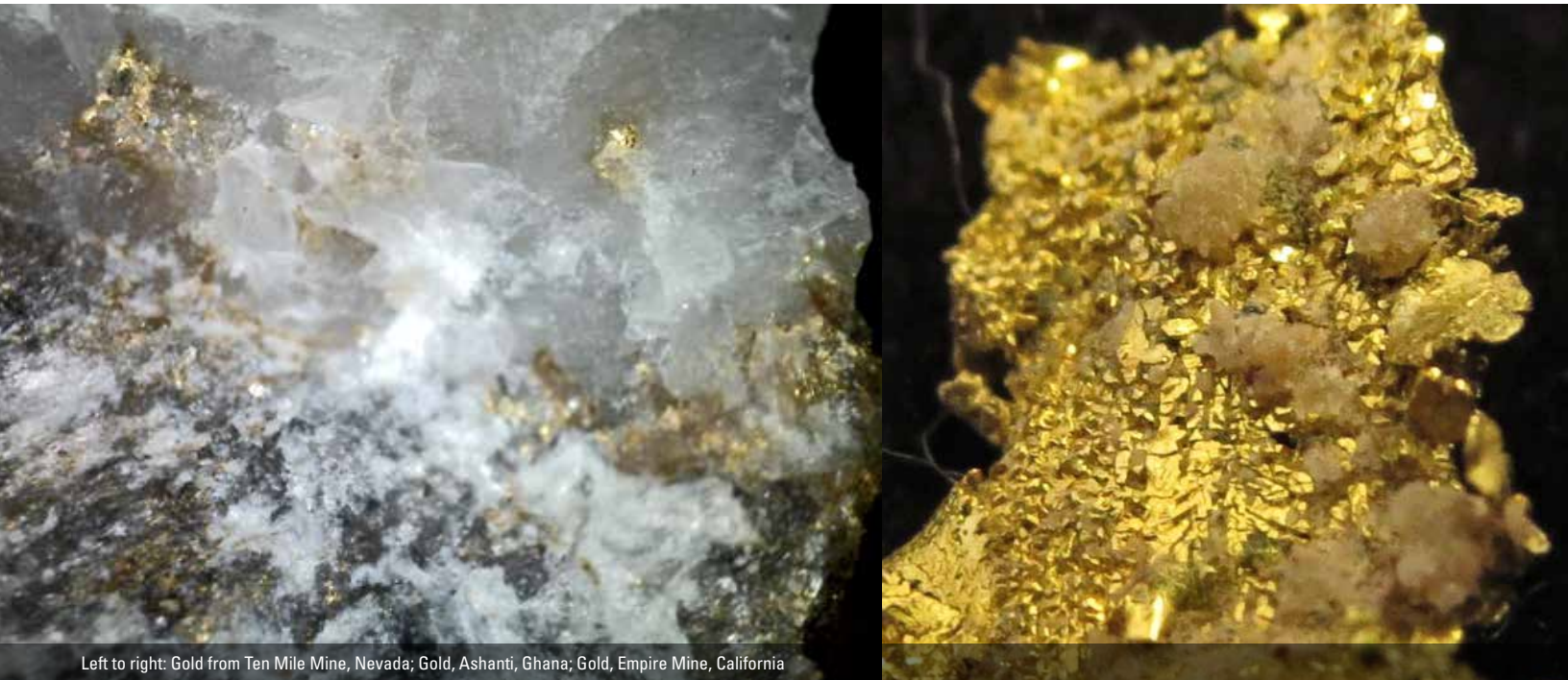
A diagnostic leach test can be very useful to qualitatively assess how gold occurs within the ore and the extent to which it may be refractory. Several different permutations of diagnostic leach tests depend on specific objectives, but they generally involve the sequential leaching of a gold ore sample with progressively stronger reagents, producing a qualitative assessment of the gold deportment within the sample. A typical 5-Stage diagnostic leach procedure includes:

Stage 1: Gravity concentration to remove the gravity recoverable gold from the sample, followed by cyanidation of the tailing to determine the cyanide leachable gold. Typically, a sample is ground and then subjected to gravity concentration with a centrifugal gravity concentrator, followed by hand-

Nature of ore at a South African gold mine

Shaft 1 Reef	Shaft 2 Reef
Narrow mineralised channel	Wide mineralised channel
Higher gold concentration on basal surface	Even distribution of gold throughout reef
Gold commonly associated with carbon	Low carbon content with no gold association
Higher gold concentration in the finer fractions	Even gold distribution throughout size fractions

Diagnostic leaching for refractory gold ores



Left to right: Gold from Ten Mile Mine, Nevada; Gold, Ashanti, Ghana; Gold, Empire Mine, California

panning, or on a Mozley-type table. The concentrate is fire assayed for gold. The gravity tailing is subjected to cyanidation and the residue is assayed for gold. Gold recovered during Stage 1 is not considered refractory. A portion of the cyanidation leach residue is advanced to Stage 2.

Stage 2: Leach residue is reacted with hydrochloric acid to dissolve labile sulfide minerals such as pyrrhotite and liberate any gold that may be associated with them. The residue is then subjected to cyanidation and a sample of the residue is assayed for gold. A portion of the leach residue is advanced to Stage 3.

Stage 3: Leach residue is reacted in a hot sulfuric acid leach to dissolve acid soluble minerals not dissolved by hydrochloric acid, such as sphalerite and reactive pyrite and other labile copper sulfide minerals,

and liberate any gold that might be locked within these minerals. The sulfuric acid leach residue is then subjected to cyanidation and a sample of the residue is assayed for gold.

Stage 4: Leach residue from Stage 3 is reacted in a hot nitric acid leach to dissolve more resistant sulfide minerals, such as pyrite and arsenopyrite, and liberate any gold that might be locked in these minerals. The residue is then subjected to cyanidation and a sample of the residue is assayed for gold.

Stage 5: Leach residue from Stage 4 is subjected to a high temperature roast to remove any carbonaceous material and then subjected to cyanidation and the residue is assayed for gold. Any gold remaining is assumed to be locked in silicates or associated with fine sulfides.

After the 5-Stage test is completed, a metallurgical balance is calculated to determine the distribution of gold recovered during each stage of the test. Gold recovered during Stage 1 would be considered non-refractory and could be recovered by standard gravity concentration. Gold extracted during the next four stages indicates minerals that the gold occurs with and suggests process options, such as pressure oxidation, biooxidation or roasting that could lead to improved recovery of the refractory gold values. Gold remaining in the Stage 5 leach residue is most likely locked or encapsulated and probably not recoverable unless adequate liberation can be achieved by finer grinding.

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