Keynote Address: Lessons learned from the copper industry applied to gold extraction

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The copper industry is cyclical with the price determined by market forces (i.e., the balance between supply and demand for the metal.) The period of each cycle typically varies between 6 to 9 years. These cycles drive decision making for exploration, new project and mine development, mine closures, process improvement, research and development, and technological innovation. The gold industry is fundamentally different from copper in that supply and demand do not, alone, determine metal price and many other factors play a key role, including global and regional financial conditions, political stability, and the global future economic outlook. However, the gold price experiences trends and longer term cycles that similarly drive business decision making.

This paper examines developments in the copper industry that have occurred over the past few price cycles (approximately 20 years) and explores how the lessons learned can be applied to gold extraction. A number of specific examples and opportunities are discussed in detail, including; technology development and innovation, cost control and business improvement, material characterization, comminution equipment, biological heap leaching, and concentrate pressure leaching.

Introduction

There have been a large number of significant developments in the copper industry over the past two decades. To a significant extent, these developments have been driven by the cyclical nature of the copper price cycle characterized by periods of strong metal price (3 to 5 yrs) followed by periods of depressed prices (3 to 5 yrs), as shown in Figure 1. As for every commodity, copper price is driven by market forces (i.e., supply and demand). Supply side growth is driven by incremental increases and major expansions at existing operations in the short term (1 to 3 yrs typically), and new capacity, through exploration and new project development in the longer term (5 to 10 yrs).

Demand decreases occur during periods of depressed prices through cut backs made at existing operations and cancellation of new development projects (and exploration). Demand is driven by a variety of market conditions, including; 1) global and regional economic conditions (often measured in terms of GDP and industrial production), and particularly economic conditions in the major copper consuming regions of the world (i.e., China, US, Europe and Japan), 2) copper scrap availability, and 3) substitution opportunities. When supply exceeds demand, the excess copper produced is placed in warehouses (LME, COMEX, Shanghai) and inventories build. When demand outpaces supply, copper is pulled from warehouses to meet the demand and inventories fall.

The ore grade of copper deposits being mined decreased significantly through the 20th century. Between 1988 and 2006, the average copper head grade declined from 1.08% to 0.84% which is a 22% drop (Brook Hunt estimates). This has driven the need to improve metal extraction efficiency through more efficient mining and processing technology, and increasing the scale of economy for operations (i.e., higher throughput and production rates). This is exacerbated during periods of depressed pricing when extreme measures must be taken by marginal producers to reduce costs and remain competitive, and as other producers strive to maintain operating cash flow margins. Improvements in operating efficiency at existing operations may be achieved in a number of ways, including the following:

- Operating cost reduction for an existing process or unit operation
- Improvement in metal(s) recovery
- Increase in throughput (and production) by de-bottlenecking and expansions
- Improvement in the quality, usually grade, of ore delivered to the process (generally a short term benefit)
- Implementation of a new technology in place of existing process
- Improvements in safety, human health/hygiene, environmental, sustainable development and social responsibility aspects.

In new development projects, there are opportunities to make improvements in operating efficiency over incumbent technology through the prudent use of new technology and equipment, provided that risk is assessed and managed effectively.

Over the course of the past two decades, significant operating efficiency improvements have been made in all of the areas listed above during this time. Price cyclical has been a major driver for many of these improvements, and a deterrent for others.

As readers are well aware, the gold market is fundamentally different from the copper market. Gold is not (yet, at least) traded as a commodity and the price depends on many factors including; global and regional financial
market conditions, worldwide, regional and national political stability; macro-scale supply and demand for the metal, and the global future economic outlook. Gold demand is principally driven by jewellery requirements (approximately 70% of total demand), mainly in Asia, which, in itself, is a function of many related and unrelated factors and sentiment.

Similarly to the copper industry, gold ore grades have declined significantly through the 20th century, providing a strong driver for innovation to reduce costs. However, the prevailing gold price fundamentally drives the need for efficiency improvements in existing operations (to maintain operating margins) and the development of new projects (and exploration activity). The gold market lacks clear price cycles which occur with reasonable periodicity in the copper industry. Furthermore, gold projects are typically shorter lived than corresponding copper projects, with higher value per ton deposits mined and processed at lower throughput rates. This means that the gold industry tends to be driven by near to medium term price projections without the expectations of supply demand driven price cycles to come.

This is a hugely important difference. As can be seen in Figure 2, the gold industry has been very successful in driving step change technology developments during periods of strong pricing. In recent history, an exceptional period of innovation occurred in the gold industry during the period 1979 to 1988 when the gold
price reached historic highs in real terms, averaging over $750 per oz during the 10 year period. New technologies introduced successfully during or immediately after that time, included heap leaching of low(er) grade ores, carbon adsorption and carbon in pulp, pressure oxidation and fluidized bed roasting of sulphide ores and concentrates, and biological oxidation. However, during times when gold price is not booming, technology development and innovation appear to go dormant and no step change developments are evident. This doesn’t mean that no innovation is occurring; clearly the gold industry works hard on improving existing processes and technology and strives for better efficiencies all the time.

Necessity is the mother of invention, but the innovation process can (and should) be managed and driven even without necessity or a ‘burning platform’. The copper industry has a ‘burning platform’ every few years. Just as the copper industry has learnt from the gold (and other) industries in the past, the gold industry can reap rewards from applying lessons learned from the copper industry over the past twenty years or so. This paper discusses a number of important developments in the copper industry that have occurred over the past two decades, and explores the relevance, and potential application, of each within the gold industry.

Major examples from the copper industry

Managing the innovation process

The innovation process cannot be turned on at the switch of a button. It has to be carefully planned and nurtured through periods of metal price fluctuation and uncertainty. Unfortunately, the innovation process can be (and sometimes is) turned off at the switch of a button. It needs to be flexible and adaptive, adjusting to the changing needs of the organization, but still advancing the core aspects of innovation that the business needs over the long term. The hallmarks of an effective innovation process are the following:

• Experienced, dedicated and self-motivated individual(s) to drive innovation and the innovation process
• A centralized applied technology development group to drive innovation
• A carefully developed strategic plan for innovation, whether it be continuous improvement or technology development
• A well coordinated, operationally focused effort, with operators involved at every step
• The areas for innovation focus must be evaluated, ranked and prioritized
• The innovation process must be communicated clearly to key stakeholders and progress updated frequently
• Most of the effort should go into the effective application of innovation and technology within the operations; fundamental research is fine (and necessary) but on its own it will not accomplish very much
• Progress on innovation should be reviewed routinely (quarterly or bi annually), and the strategic plan updated regularly (annually) to reflect changes in business need and conditions
• Timely ‘go, no go’ decisions are made on each initiative (sometimes using a stage-gate process)
• In my experience, less than 5% of your people come up with 99% of the innovation – find out who they are and put them in roles that maximize their contributions.

There is a great deal of variation in how the innovation process has been managed among major copper producers. The producers with the best track record in innovation (including Freeport-McMoRan, Codelco, Rio Tinto and BHP-Billiton) have been able to; 1) dedicate appropriate resources (i.e. people and money), through metal price cycles, 2) have demonstrated the desire and drive to adopt innovation within their operations, and 3) have a senior executive management team and board that understands the critical importance of innovation to be competitive over the long term (rather than managing solely for quarter by quarter results at the expense of longer term value creation). The enlightened few have recognized the opportunity for sustainable, competitive advantage through effective innovation. A similar philosophy must be applied to innovation that is used for exploration and development to grow a prosperous mining company for the long term.

The gold industry can benefit significantly from needs well planned and well executed innovation and technology development processes.

Cost control and business improvement processes

During periods of depressed metal price, producers must take actions to contain and reduce operating costs, and take other actions necessary to ensure competitiveness and maintain operating margins. Sometimes, this comes at the expense of foregoing maintenance and equipment replacements on the planned schedule. Several copper producers have implemented formal cost improvement initiatives, such as ‘continuous improvement’, ‘six sigma’ and ‘lean production’, in order to institutionalize the cost improvement processes and methods within the organization. The hallmarks of these cost improvement initiatives are: 1) establishing leadership and accountability for the cost improvement initiative; 2) determining what process will be used; 3) defining how the initiative will be executed and rolled out into operations, 4) establishing metrics to measure progress, 5) setting a timeline for execution, and 6) measuring and communicating the results of the initiative on a regular basis.

In the copper industry, the use of teams to indentify rank and prioritize opportunities for improvements within the business has proven to be an excellent approach to this. Teams are typically comprised of individuals from across the organization and are set up to focus on a particular issue or set of related issues. It is important to heavily weight the teams towards operational and technical expertise, but other key resources should also be included, such as; supply chain procurement representatives, human resources, information technology, environmental, safety and health. The team reviews performance and costs in a given area,brainstorms the opportunities and options for cost reduction, researches the opportunities and options in detail, prioritizes which options should be tackled and in what order, develops an execution plan and, most importantly, follows up on the execution. Areas of focus are generally divided up by business area (e.g. mining, milling, leaching, flotation, smelting, etc), or by cost center (e.g. energy, steel, labor, reagents, water, maintenance supplies, operating supplies), or by some other division that makes sense for the business. Alternatively, focus areas can be selected in a way that forces people to look at the business from a different (and fresh) perspective.

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Another important aspect of continuous business improvement is the identification and specification of best practices. Most producers, whether copper, gold or other metals or minerals, believe that they are utilizing best practices. However, few producers go through a formal process to determine what these practices are and whether they are actually using the best practice. A best practice can be something as simple as the procedure for cleaning out a copper electrowinning cell or the procedure for eluting gold off carbon. In either case, it is possible to have a procedure that gets the job done, however if the procedure does not represent best practice then the operation is incurring additional costs (or losing revenue). If a non optimal procedure is used for clean out of the copper EW cell, the result may be production of off specification copper cathode. For the carbon elution example, lack of a best practice procedure could result in a significant loss of gold on carbon fines or incomplete stripping of gold within the time available.

You don’t need a best practice for everything. But you do need best practices for all of the critical, operational steps. These need to be formally identified, written down clearly and concisely for all to read and understand, and implemented company-wide.

Whenever I visit an operation and we are investigating a particular problem, I generally ask the following questions:

- What is your procedure for this?
- How would a new operator know how to do this (i.e. is it written down)
- Is it best practice?
- How do you know it is best practice?

I am often surprised by the answers. Either the operator knows the procedure, shows me a written version and knows that they have a best practice in this area. In this case, they nearly always teach me something I didn’t know. They are on top of the issue and we move on to the next issue. Alternatively, the operator has a general idea of the procedure, but cannot find it in writing and has no idea whether not it is best practice. Worse still, when you look to clarify the procedure with other operators and managers, there is further lack of agreement and clarity. I rest my case.

Material characterization; a core competency in our business

Until recently, the need for effective material characterization has been hugely under appreciated in the copper industry. In the 1980s and 90s, copper porphyry deposits were characterized by geological logging of core and drill chips, coupled with chemical analysis to provide total and acid soluble copper assays, and assays for other metals (by-products such as Au, Ag and Mo, or bad actors such as As, Sb, Se etc.). The use of mineralogical techniques, (e.g. optical microscopy, x-ray fluorescence, x-ray diffraction), or other more sophisticated techniques, was reserved to address special problems or concerns and was rarely employed. This was the domain of universities and specialist institutions.

The emergence of new tools that allow rapid and accurate analysis of representative samples of materials has revolutionized material characterization in the copper industry. These techniques include the following:

- automated scanning electron microscopy (e.g. QEMSCAN and mineral liberation analyzer) for mineral identification, grain size, mineral grain intergrowths, liberation and locking characteristics
- automated XRD for quantitative mineralogy
- automated XRF for quantitative elemental analysis
- near infrared (NIR) for quantitative clay and clay-forming mineral analysis.

These techniques are illustrated schematically in Figure 3. The techniques shown in Figure 3 are now applied routinely, but with varying frequency and intensity, in three areas of our business as follows:

- ore deposit characterization and modeling for mine/process design
- routine production control
- Metallurgical problem solving, troubleshooting and optimization.

For each area of the business, a plan must be developed for what to measure and how often to measure it. For example, for ore deposit characterization metal assays are obtained for each sample interval. Mineralogical attributes can, generally, be measured on a small portion of the sample intervals (e.g. one in 20 or one in 50), depending on
the distribution and variability of the mineral(s) of interest. Alternative mineralogy can be performed on sample composites. The same is true for routine production control and for metallurgical problem solving and optimization. While rigorous statistical approaches can be used to determine the frequency of mineralogical analysis, general guidelines and rules of thumb can be developed for each deposit or project fairly quickly and easily.

One key learning issue from the copper industry is that the new mineralogical techniques provided a huge amount of data. When planning material characterization requirements for each segment of the business, it is critical that the purpose and use of the information is considered and agreed to by all stakeholders up front. Just because we can measure something, does not mean that we should measure it. A good example of this is the use of QEMSCAN in a copper production environment. The QEMSCAN can provide an overwhelming amount of data from a single sample. The key information for one particular copper porphyry operation is what is the amount of chalcopyrite, chalcocite and pyrite in the material and how are these minerals related to each other (grain size and locking). If the focus of the material characterization work is limited to these species, the information can be assimilated and communicated to operating staff in a meaningful and manageable way.

Other techniques such as down hole neutron probe analysis and cross belt neutron activation analysis are now being tested in the copper industry and showing much promise.

In a historical perspective, the mineralogy and metallurgy of porphyry copper deposits is, generally, significantly more complex than gold deposits, and this is certainly the case for non refractory gold ores which can be processed directly by cyanidation. However, this is changing as the availability of free milling and oxidized gold ore deposits decreases over time. Increasingly, the gold industry is turning to the development of more refractory deposits (with gold associated with sulphide and carbonate minerals) and to more complex copper gold ores. This increased mineralogical complexity requires a much more rigorous approach to material characterization.

Secondly, emerging mineralogical techniques provide opportunities for better ore type classification and improved interfacing between mining and processing operations. A good example of this is the use of near infrared measurement to determine clay and clay forming mineral content ahead of heap leaching operations. This allows for improved blending in the mine and between the mine and the process to control and manage clay content, ensuring good permeability and performance within the heap. In some cases, material with excessively high clay content must be rejected to the waste stockpiles rather than be delivered to the process. This is the case at the Morenci operation in Arizona where secondary copper sulphide (chalcocite) ore is processed by three-stage crushing followed by biological heap leaching with sulphuric acid.

**Comminution – optimum grind size versus cash flow**

There are three main aspects of comminution that warrant discussion in this paper. The first, considers the question of grind size optimization versus cash flow maximization. For some time, it appears that the copper industry focused on dry grinding equipment to achieve the optimum grind size. The additional cash flow from additional metal production almost always exceeds the value of the recovery loss due to the coarser grind size. It is the job of the plant metallurgist and plant management to make sure that, if a decision is made to operate at higher throughput, grinding equipment is rapidly upgraded or expanded to get the plant back to the design optimum grind size. Failure to do this in a timely manner results in misuse of the resource in the ground and loss of shareholder value over the life of the resource.

Let us look at the example of the Chino copper concentrator in New Mexico. The optimum grind size for the resource was 80% minus 150 microns – this was the original plant design specification. In the 1980’s, as a result of operational improvements and de bottlenecks, the plant was operating to maximize throughput with an actual grind size of 80% minus 300 microns. The recovery difference for these two grind sizes was about 8 to 9%. The circuit consisted of primary crushing, SAG milling, two-stage crushing of SAG mill discharge oversize, ball milling, and flotation to produce copper and molybdenum concentrates. Plant management had the choice of reducing throughput (and consequently metal production) or adding grinding equipment to achieve the optimum grind size. The choice was made to install a tertiary stage of grinding (following the existing ball mills) using Metso Vertimills. Four Metso VTM 1250 units were installed and grind size close to optimum was achieved.

Many other copper concentrators, particularly older facilities, have upgraded their grinding circuits and made adjustments to operating strategies in recent years to get back to the optimal grind size for the resource.

**Comminution – high pressure grinding rolls**

The second aspect of comminution considers the use of high pressure grinding rolls (HPGRs) as an alternative to SAG milling in large copper (and gold) operations. Until recently, HPGR technology has been confined to application in the cement, diamonds and iron ore industries. In 2004, Freeport McMoRan (previously Phelps Dodge) made the decision to install HPGR’s in place of SAG mills for a 108,000 mt/d concentrator at Cerro Verde near Acrequipa in Peru. The plant uses four 2.4 m diameter by 1.6 m long HPGR units supplied by Krupp Polysius and fitted with two 2 500 kW drives. Each HPGR is configured in series with a double deck vibrating screen. The screens are operated wet to ensure break down of any eaked material generated by the HPGR’s, and this is a key design feature of the circuit. Screen deck oversize material is recycled back to the HPGR feed bins. The plant was constructed at a cost of approximately $850 million (2007 US dollar basis) and was commissioned in late 2007. The flowsheet, testwork, and design basis for this circuit has been reported elsewhere. The plant is operating at design throughput and close to design availability.

The key drivers for the decision to use two-stage crushing, HPGR’s and ball milling instead of conventional primary crushing, SAG and ball milling were: 1) significant operating cost savings of $0.37/mt based on a reduction in

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electrical power of 4.2 kWh/mt and lower steel consumption, 2) manageable risk associated with the technology implementation at a large scale, and 3) an increase in capital cost for the plant to provide in-surance for equipment and plant availability. The overall energy consumption, including the energy equivalent of the wear steel (grinding balls and mill liners) for a generic circuit employing HPGR’s in place of SAG milling, has been estimated to be 9 kWh/mt. The technical risk for the ‘new’ application of HPGR technology to treat copper ore was managed through a combination of pilot scale testwork (at Krupp Polysius in Germany), effective and thorough material characterization of the deposit, meticulous metallurgical oversight throughout the design phase, and experience gained at other operations around the world who were willing to share their experiences.

Freeport-McMoRan also installed HPGR’s as a fourth stage of crushing in the C1 and C2 concentrators at Grasberg in Indonesia. The primary purpose of the HPGR installation was to reduce the flotation circuit feed particle size and thereby increase copper and gold recovery. This application allowed the copper and gold production to be increased by 5% and 4%, respectively, in the two concentrators. These units have been operating successfully since 2008.

HPGR’s represent a significant opportunity for gold producers as alternatives to SAG mills in comminution circuits. However, more importantly, HPGR’s provide an opportunity to generate heap leach feed material that has improved characteristics for leaching (better liberation along fractures and zones favoring mineralization, and less fines generation for better heap permeability. The copper industry is pursing this for a variety of sulphide and oxide leaching applications.

**Comminution: high pressure grinding rolls and stirred mills in series**

The prior discussions on HPGR and Vertimill applications leads to the following question: why not combine the HPGR and stirred milling in a single grinding circuit to take advantage of the higher energy efficiency of both units compared with the incumbent conventional technology? Stirred milling is estimated to be 20 to 30% more efficient than conventional ball milling, particularly at finer sizes (<35 mesh; 500 microns). It is estimated, that this could reduce the overall equivalent energy consumption for grinding by between 10 to 12 kWh/mt, compared with a conventional SAG ball mill circuit [10], however, this is ore type dependent. About half of this equivalent energy consumption is electrical energy and the other half is grinding steel (balls and liners) expressed as an energy equivalent.

**Biological heap and stockpile leaching**

Biological oxidation processes have been utilized for leaching of secondary sulphide (chalocite dominant) copper ores at run of mine size for over a century. Prior to the 1950’s, the role of bacteria in the process was not understood or appreciated. By the 1970’s, many operations treating porphyry copper ores containing appreciable amounts of oxide and secondary sulphide were leaching low grade materials in run of mine stockpiles.

Tremendous advances were made in biological heap leaching of crushed secondary sulphide copper ores in the 1990s and early 2000s. Following the first modern day crushed ore heap leach at Pudahuel in Chile, a number of large scale, but relatively low grade, crushed ore heap leaching operations were established at Cerro Colorado, Quebrada Blanca and Zaldívar in Chile, at Cerro Verde in Peru, Girilambone in Australia, and at Morenci in Arizona, USA. The ability to, successfully, heap leach low grade copper ores and to achieve acceptable metal extraction was made HPGR’s in place of technical advances:

- The development of stacking equipment that could place crushed ore onto a heap without creating excessive compaction and to maintain effective permeability within the heap
- The development of forced air injection techniques employing blowers and distribution piping beneath and within the ore heap
- The use of controlled solution application rate to the heap to promote bacterial activity and growth and to optimize copper extraction
- The control of solution chemistry (acid and ferric/ferrous) in the leach solutions to promote bacterial activity and growth.

These technical advances made it possible to achieve copper extractions of 75 to 80% from chalocite-dominant ores within short time frames (12 to 18 months), significantly higher than the typical extractions of 40 to 50% obtained from stockpile leaching of these materials at run-of-mine size over much longer time frames (3 to 4 years).

More recently, additional advances are in progress, including: genetic mapping of bacteria that are active in copper sulfide leaching; identification of the role and function of different bacterial strains in the leaching process; development of methods to enhance the number and activity of bacteria that perform critical, rate-determining steps in the process; and development of bacterial inoculation and augmentation techniques.

Finally, significant strides have been made in technology to process primary copper sulphides containing chalcopyrite, bornite and pyrite. Chalcopyrite is quite refractory to atmospheric acid leaching processes, even in the presence of ferric and active iron oxidizing bacteria, because of the formation of a passivating poly sulphide layer on the surface. Based upon experience at operations in the USA and Chile, copper extractions achieved from large, low grade run of mine stockpiles in which chalcopyrite is the major copper mineral are typically about 10 to 15% over a five (5) year period. However, the leaching rate of chalcopyrite can be significantly enhanced by elevating temperature and or by controlling solution potential within the stockpile or heap. Elevated temperatures can be achieved within heaps and stockpiles by oxidizing pyrite contained in the ore. The conditions required for effective pyrite oxidation include: sufficient liberation of pyrite to allow access to aerated solution, adequate iron in solution, solution conditions for bacterial activity (pH, no excess concentrations of deleterious species in solution), sufficient quantity of material (and pyrite) to generate and maintain heat within the stockpile, well managed irrigation rates, and effective aeration of the heap or stockpile.

It should be noted that the primary copper mineral bornite is less refractory than chalcopyrite, and can be leached using similar techniques to those applied for chalcocite-dominant ores, albeit with lower copper extractions achieved (50 to 60%) after three-stage crushing.

Another important aspect of the development of effective biological heap and stockpile leaching processes is the ability to model and predict behaviour within the heaps and...
stockpiles. There are two reasons for doing this and, in the author’s opinion, these reasons, sometimes, become confused and conflicting. Firstly, all heap and stockpile leaching operations need a production model that can be used to measure leaching performance and production, as well as to forecast future production. Generally, such models are based on empirical information (actual production data and the results of metallurgical tests and other information). Secondly, in order to understand and improve the leaching process within the heap/stockpile, we need to develop models that adequately describe the most important physical and chemical processes that occur. This latter model can be described as a phenomenological model. Tremendous advances have been made in phenomenological modeling of heaps and stockpiles, and in some cases, these models have been calibrated against real operating heaps and stockpiles. While these models are not perfect, they allow the user to examine the effects of many variables and to apply the results to the design and optimization of heap leaching operations. Excellent examples of the application of such phenomenological models include: effects of air injection rate, air injection piping spacing and aperture spacing, effects of solution application rate and cycle (including on off pulsing), effect of rate of pyrite oxidation, effect of ferric ion and total iron concentrations, and many other factors.

The gold industry has been applying bacterial oxidation to treat refractory and semi refractory gold ores for many years. However, the application of bacterial oxidation to heap and stockpile leaching has been limited to a few niche applications (e.g. in Nevada and Ghana). There is an opportunity to tap into bio heap and stockpile leaching technology and expertise from the copper industry to allow large scale processing of low grade refractory and semi refractory ores.

**Concentrate leaching of copper-gold concentrates**

The copper industry, and specifically Freeport McMoRan, has made great strides in the application of pressure leaching technology to treat copper sulphide (mainly chalcopyrite) concentrates. To a significant extent, this work built on developments in the gold industry in the 1980’s and 90’s with pressure oxidation circuits installed at McLaughlin, Mercur, Getchell, Goldstrike, Lone Tree and Twin Creeks (all in the USA), Sao Bento (Brazil), Porgera and Lihir (Papua New Guinea), and Campbell Red Lake (Canada). In 2003, the world’s first high temperature (225°C) pressure leaching circuit was commissioned at Bagdad, Arizona, to treat approximately 55,000 metric tons per year of chalcopyrite concentrate. The process was integrated with the existing low grade oxide stockpile leaching, SX and EW operation at the site, and the high grade pressure leach solution was blended with lower grade stockpile leach solution. Essentially, all of the sulphide sulphur in the concentrate was converted to sulphuric acid and was utilized beneficially in the stockpile leaching operation. Copper recovery in excess of 98.5% was achieved. The Bagdad concentrate contained minor quantities of gold and silver, but not sufficient amounts to justify the installation of a cyanide leaching facility to treat the pressure leach residue. However, testwork was conducted on the pressure leach residue and the recovery of gold and silver was determined to be technically feasible.

In 2007, a medium temperature (160°C) pressure leaching circuit was commissioned at Morenci in Arizona to treat 200,000 metric tons per year of copper concentrate. In this case, the advantage of medium temperature was the conversion of a significant portion of the sulphur in the concentrate to elemental sulphur. This was done to match the amount of sulphuric acid generated by the pressure leaching process with the acid requirements at the Morenci site for heap leaching of secondary copper sulphide ore. The medium temperature pressure leaching process required the results of finely grinding the concentrate to 80% minus 7 μm and 98% minus 15 μm.

In 2008, changes were made to the Morenci mine plan that resulted in a significant increase in the amount of acid required for heap leaching. As a result of the changes, the process was converted to operate at high temperature (210°C).

These concentrate leaching developments, present opportunities for application to sulphide-bearing gold-copper and copper gold deposits worldwide. Several flowsheets have been developed by Freeport McMoRan for these applications. An example of one of these is shown in Figure 4 for high temperature (215 to 225°C) pressure leaching in conjunction with heap, stockpile or agitated tank leaching of oxide or secondary sulphide ore to utilize the acid generated by the pressure leaching circuit.

In the flowsheet in Figure 4, pressure leaching is performed at 215 to 225°C using an oxygen overpressure of 120 to 200 psi. After leaching, the copper-bearing leach solution is separated from the solids by counter-current decantation (CCD). The solution is combined with low grade leach solution from the heap stockpile tank leaching operation which itself processes oxide or secondary sulfide copper ore (usually lower grade material). The ratio of heap stockpile tank leach solution to pressure leach PLS (the dilution ratio) is 8:1 in the example shown. Copper is recovered from leach solution by solution extraction (SX) and electrowinning (EW). The copper leach residue is neutralized with lime (and/or limestone), the pH adjusted to 10.5 and then the slurry is leached with cyanide to extract gold. If there is sufficient (economic value of) silver present in the ore, then a hot lime boil needs to be utilized to break down the silver jarsite formed during pressure leaching and to render the silver amenable to cyanide leaching. Gold and silver are recovered by carbon adsorption.

It is possible, also, to consider stand alone flowsheets for pressure leaching of copper gold ores without heap or stockpile leaching operations included. Such a flowsheet is shown in Figure 5. However, in such a case all of the acid generated by pressure leaching must be neutralized (representing a significant cost) and, essentially, all of the solution must be recycled to the process and/or retreated for metals removal.

Another alternative for pressure metals recovery, particularly from the elemental sulphur-bearing medium temperature pressure leaching residue, is the potential use of thiosulphate leaching technology. There are still a number of hurdles to be overcome with bringing this to reality, including the effective recovery of gold and silver from solution, and management of thiosulphate oxidation rate and consumption, but this is clearly an area for future study and consideration.

**Conclusions**

This paper has examined several examples of efficiency improvement and innovation in the copper industry over the past two decades. All of these have potential application to the gold industry. Some of these are already in the process of being implemented in gold operations and projects, while...
others present opportunities for the future. In most cases, the significant step change developments in the copper industry have grown out of well planned and well managed technology development and innovation initiatives.

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**References**


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Twenty-seven years of broad international experience managing major, innovative copper, gold, molybdenum and cobalt operations and projects in the USA, Chile, Peru, Mexico, South Africa, and the Congo (DRC). Marsden has held various operations and technical management positions during nine years with Consolidated Gold Fields plc and eighteen years with Freeport-McMoRan Copper & Gold Inc. (formerly Phelps Dodge). Author of “The Chemistry of Gold Extraction” (1st and 2nd editions).