

How will biomining be applied in future?

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Abstract: This paper reviews the current status of commercial biomining operations around the world, identifies factors that drive the selection of biomining as a processing technology, describes challenges to exploiting these innovations, and concludes with a discussion of biomining's future. Biomining is commercially applied using engineered dumps, heaps and stirred tanks. Overcoming the technical challenges of lowering costs, processing low-grade, low-quality and complex ores and utilizing existing capital investments at mines requires better understanding of microbial activities and innovative engineering. Surmounting biomining commercial challenges entails improved mining company/biomining innovator cooperation and intellectual property control.

Key words: biomining; dump bioleaching; heap bioleaching; continuous stirred-tank bioleaching

1 Introduction

“Biomining is a generic term that describes the processing of metal-containing ores and concentrates using (micro-)biological technology”[1]. Biomining has application as an alternative to more traditional physical-chemical methods of mineral processing.

The modern era of bioleaching began with the discovery of the bacterium, *Thiobacillus ferrooxidans* (now *Acidithiobacillus ferrooxidans*) in the mid-1940s and the initial understanding of this microbe's involvement in copper extraction. In 1958 Kennecott Mining Company patented the use of *Thiobacillus ferrooxidans* for copper extraction and applied the biohydrometallurgical process to extract copper from run-of-mine (blasted, but uncrushed), low-grade copper ores from the Bingham Canyon Mine near Salt Lake City, Utah, USA[2].

Today biomining is widely practiced commercially throughout the world to enhance the extraction of gold from ores and mineral concentrates in which the precious metal is locked within a sulfide mineral, to extract copper from secondary copper ores, and, on a more limited basis, to leach base metals other than copper from ores and concentrates.

In this work, the current status of commercial biomining operations around the world is reviewed,

factors that drive the selection of biomining as a processing technology are identified, challenges to exploiting these innovations are described, and conclusions are drawn with a discussion of biomining's future.

2 Today's applications of biomining

Biomining is commercially applied using three different engineered methods: dump bioleaching, heap bioleaching/biooxidation, and stirred tank bioleaching/minerals biooxidation. Bioleaching usually refers to biomining technology applied to base metals; whereas, minerals biooxidation is often applied to biomining applied to sulfidic-refractory gold ores and concentrates. However, in the technical literature the terms are frequently used interchangeably.

2.1 Dump bioleaching

First commercially applied 50 years ago, dump bioleaching remains an important process for the copper mining industry. At many open pit operations a very large amount of material is of too low grade to sustain the cost of flotation and smelting, so this marginal-grade ore (typically less than 0.5% copper) is fractured by blasting in the pit and hauled as large rock fragments to dumps. Dumps contain millions of tonnes of run-of-mine ore and are often more than 60 m deep. Acidified water

is applied to the top surface of the dump using sprinklers or drippers. As the solution percolates through the dump, favorable conditions develop for the growth of naturally-occurring microorganisms, which catalyze the oxidation of the copper sulfide minerals.

Leaching of copper from dumps is measured in decades, because of the large particle size of the marginal-grade ore placed in them, inefficiencies in solution transport through the dump, and generally poor aeration that limits microbial activity. The copper is dissolved in the leach solution and percolates to the base of the dump where the copper-containing leach solution is collected and directed to a solvent extraction/electrowinning(SX/EW) process for production of copper cathodes. Raffinate from the SX circuit is recycled to the top of the dump.

Dump bioleaching continues to be a highly economic method of recovering copper from very low-grade ores, because of the large tonnages of copper-containing rocks that can be processed and because of the low production costs. The dump bioleach operation initiated in 2006 by BHPBilliton at the Escondida Mine in Chile includes technical enhancements to improve microbial activity and increase the rate and overall recovery of the copper. The Escondida dump bioleach is expected to produce 180 000–200 000 t of cathode copper per year over the next 40 years, making Escondida the largest dump bioleach operation in the world.

With the many technical enhancements that are currently being applied to the practice of dump bioleaching of marginal-grade copper sulfide ores— aeration, pre-conditioning of the ore with acidified ferric iron solutions, and in some cases, crushing—the distinction between dump bioleaching and heap bioleaching is being blurred.

2.2 Heap bioleaching

Biomining is commercially applied to heap leach copper sulfide ores and to “pre-treat” gold ores in which the gold is occluded in sulfide minerals.

Heap bioleaching is widely practiced around the world for the extraction of copper from “secondary copper ores”, which contain the mineral chalcocite (Cu_2S) and covellite (CuS), the latter a by-product of chalcocite leaching. The ore is crushed to about 19 mm or less and agglomerated in rotating drums with acidified water to condition the ore for the microorganisms and also to affix fine particles to the larger rock particles. The ore is conveyed to specially engineered pads where it is stacked. The pads are lined with high-density polyethylene(HDPE) and perforated plastic drain lines

are placed on the pad to improve the drainage of copper-containing solution from the bottom of the ore heap. A coarse rock layer is placed above the drain lines and within this rock layer a network of perforated plastic air lines is arranged. Air is forced through the air lines and directed to the microorganisms in the heap by blowers external to the heap. The ore is stacked to a depth of 6–10 m most often with automated stackers. The ore is irrigated with acidic raffinate—the effluent from the solvent extraction facility where the copper is recovered from the solution and formed into cathodes. With acidic conditions and abundance of sulfide minerals and iron, naturally-occurring microorganisms develop within the ore heap (numbers exceed 10⁶ per gram of ore), facilitating copper extraction. The maximum copper leached from heap bioleach operations is 80%–90% requiring 250–350 d of on-pad leaching to achieve this recovery[3].

The principal advantages of heap bioleaching is the rapid start-up and commissioning of operations, low capital and operating costs, the absence of any toxic emissions and the minimization or complete elimination of any water discharges because all solutions are recycled.

Heap bioleaching of copper accounts for some 7% (about 10⁶ t/a of the total global annual production of approximately 1.7×10^7 t of copper. Table 1 lists both historical and current industrial, copper heap bioleach operations[4]. This does not include copper recovered using dump bioleaching processes. It is estimated that if dump bioleaching is included some 20%–25% of the world’s copper production is attributable to bioleaching.

In 1999 Newmont Mining Corporation began commercially applying heap leach technology to pre-treat “sulfidic-refractory” gold ores[5]. These are ores in which microscopic gold particles are locked, or occluded, within a sulfide mineral, usually pyrite, arsenopyrite, or both. To obtain acceptable gold recovery the sulfide minerals must be oxidized before the ore can be treated with cyanide or other reagent that dissolves the gold. Heap biooxidation pretreatment is an engineered process to oxidize the sulfide minerals in the ore before cyanide treatment. It is similar to heap bioleaching for copper sulfide ores, but there are notable differences. After the ore is crushed, it is inoculated with three groups of microorganisms—mesophilic bacteria, moderately-thermophilic bacteria, and extremely thermophilic Archaea. Initially the inoculum is grown in a tank farm, but after the heap biooxidation facility is operating, the solution draining from the heaps contains the organisms and is used as the inoculum. The inoculation is done on a conveyor belt; alternatively inoculation could be done

Table 1 Industrial heap bioleaching operations for secondary copper ores and mixed oxide/sulfide ores throughout world (Copper dump bioleach operations are not included)[4]

Industrial heap bioleach plant and location/owner	Cathode copper production/(t·a ⁻¹)	Operational status
Lo Aguirre, Chile/Sociedad Minera Pudahuel Ltda	15 000	1980–1996 (mine closure due to ore deposit depletion)
Mount Gordon (formerly Gunpowder), Australia/Western Metals Ltd.	33 000	1991–Present
Mt. Leyshon, Australia/(formerly Normandy Poseidon)	750	1992–1995 (stockpile depleted)
Cerro Colorado, Chile/BHPBilliton	115 000	1993–Present
Girilambone, Australia/Straits Resources Ltd & Nord Pacific Ltd.	14 000	1993–2003 (ore depleted)
Ivan-Zar, Chile/Compañía Minera Milpro	10 000–12 000	1994–Present
Punta del Cobre, Chile/Sociedad Punta del Cobre, S.A.	7 000–8 000	1994–Present
Quebrada Blanca, Chile/Teck Cominco Ltd.	75 000	1994–Present
Andacollo Cobre, Chile/Aur Resources, del Pacifico & ENAMI	21 000	1996–Present
Dos Amigos, Chile/CEMIN	10 000	1996–Present
Skouriotissa Copper Mine (Phoenix pit), Cyprus/ Hellenic Copper Mines	8 000	1996–Present
Zaldivar, Chile/Barrick Gold Corp.	150 000	1998–Present
Lomas Bayas, Chile/XSTRATA plc	60 000	1998–Present
Cerro Verde, Peru/FreeportMcMoran & Buenaventura	54 200	1997–Present
Lince II, Chile/	27 000	1991–Present (sulfide bioleaching since ~1996)
Monywa, Myanmar/Ivanhoe Mines Ltd, Myanmar No.1 Mining Enterprise	40 000	1998–Present
Nifty Copper, Australia/Straits Resources Ltd.	16 000	1998–Present
Equatorial Tonopah, Nevada/Equatorial Tonopah, Inc.	25 000 (projected)	2000–2001 Failed
Morenci, Arizona/FreeportMcMoran	380 000	2001–Present
Lisbon Valley, Utah/Constellation Copper Corporation	Projected at 27 000	2006–Present
Jinchuan Copper, China/Zijin Mining Group Ltd.	10 000	2006–Present
Spence, Chile/BHPBilliton	200 000	Commissioned 2007
Whim Creek and Mons Cupri, Australia/Straits Resources	17 000	2006–Present

using an agglomerating drum. The crushed and inoculated ore is stacked on HDPE-lined pads with aeration and drain lines.

As the pyrite and arsenopyrite minerals oxidize, heat is generated and the heaps heat to above 60 °C. The microbes perform in succession: as the heap heats to above the range at which one group of microbes performs the next group of microbes takes over. The heap cools when the sulfide minerals are depleted.

The heap is removed from the leach pad when biooxidation is complete and lime is added to condition the biooxidized ore for cyanide leaching either in a heap or in a mill to extract the gold.

2.3 Stirred-tank minerals biooxidation and bioleaching

Aerated continuous stirred-tank reactor (CSTR)

minerals biooxidation/bioleaching is usually applied to mineral concentrates, because of the capital and operating costs associated with this technology. CSTR technology is carried out in a series of large stainless steel tanks (bio-reactors), each as large as 1 380 m³. Tanks are equipped with agitators that keep the finely-ground sulfidic-refractory gold concentrate in suspension and ensure that oxygen and carbon dioxide are efficiently transferred into the solution for the microorganisms which number over 10⁹ per milliliter of solution. Once the CSTRs are inoculated with the microorganisms no additional inoculation is needed, because the process is continuous. Air, provided by blowers, is introduced below the agitator impeller. Internal coils through which cooling water is circulated are mounted along the inside walls of the tanks. The time required for the biooxidation of the concentrate across all reactor stages is 3–5 d[6].

For sulfidic-refractory gold concentrate feed, the metal value is in the solid residue exiting the last reactor in the series. This residue slurry is rinsed with fresh water, neutralized with lime, subjected to solid/liquid separation and the solid residue is cyanide leached to extract the gold. Gold recoveries are in the 95%–98% range. If the mineral concentrate is a base metal, the metal of value is dissolved in the leach solution. In this case the solid residue is discarded in an environmentally-approved tailings impoundment and the solution is subjected to further processing to recover the metal value.

Table 2 lists current and historical, industrial-scale stirred-tank biooxidation plants throughout the world that pre-treat sulfidic-refractory gold concentrates. Also listed is the only stirred-tank bioleach plant for base metal extraction. The plant at Kasese Cobalt Company Limited in Uganda recovers cobalt, nickel, copper and zinc.

3 Motivating factors for biomining applications

In recent years factors affecting the production of metals on a global scale include:

- 1) Demand for a range of metal commodities, largely driven by industrialization and urbanization of China;
- 2) Discovery of ore deposits that are more difficult to exploit;
- 3) Longer and more difficult environmental

permitting process;

- 4) Higher capital costs, which are in part due to the increasing cost of steel;
- 5) Shortages of key construction materials;
- 6) Higher operating costs, in part due to increasing energy costs;
- 7) Lack of skilled labor; and
- 8) Technological challenges.

These factors drive the need for hydrometallurgical innovation and biomining in particular. Specifically the mining industry seeks to:

- 1) Avoid costs associated with smelting and refining. Transportation costs, NSR (Net Smelter Return) royalties, and penalty charges by smelters for impurities can significantly reduce the value of a resource. With onsite processing high purity metals can be produced and sold for higher value than concentrates. Valuable by-products including gold, silver and PGMs can also be recovered during on-site processing.
- 2) Process low-grade mineral concentrates that can not be economically shipped or processed by smelting.
- 3) Reduce acid costs. Acid costs for heap leaching have typically been in the US\$ (10–15) /t (2008 costs) range. However, recently acid costs have increased to more than US\$ 100 /t (delivered) and over US\$ 140 /t (delivered) in parts of Australia[7]. These costs are an incentive for oxidizing sulfide minerals for on-site production of sulfuric acid.
- 4) Process polymetallic mineral deposits, which have a complex mineralogy and are by their nature

Table 2 Industrial aerated continuous stirred-tank bioleach operations

Industrial stirred-tank biooxidation/bioleach plant, location and owner	Design capacity/t	Operating years
Fairview, Barberton, South Africa/Barberton Mines Ltd.	55	1986–Present
Sao Bento, Brazil/Eldorado Gold Corp.	380	1991–Present
Harbour Lights, Western Australia	40	1991–1994
Wiluna, Western Australia/Agincourt Resources Ltd.	158	1993–Present
Ashanti, Obuasi, Ghana/AngloGold Ashanti Limited	960	1994–Present
Youanmi, Western Australia/Golder Resources	120	1994–1998
Kasese, Uganda/Kases Cobalt Company	250	1999–Present
Tamboraque, San Mateo, Peru/Iamgold Corp. and Minera Lizandro Proano SA	60	1998–2003 (Restarted in 2006)
Beaconsfield, Tasmania, Australia/Beaconsfield Gold NL	~70	2000–Present
Laizhou, Shandong Province, China/Sino Gold Ltd.	~100	2001–Present
Suzdal, Kazakhsan/Celtic Resources Holdings Ltd.	196	2005–Present
Fosterville, Victoria, Australia/Perseverance Corporation, Ltd.	211	2005–Present
Bogoso, Ghana/Golden Star Resources	750	2006–Present
Jinfeng, China/Sino Gold Ltd and Guizhou Lannigou Gold Mine Ltd.	790	2006–Present
Kokpatas, Uzbekistan/Navoi Mining and Metallurgy	161 069	2008–Present

difficult to treat by alternative metallurgical processes including smelting.

5) Utilize existing capital investment. Many copper operations already have SX-EW plants that represent a significant capital investment. These plants can be adapted and expanded to include copper from dump and heap bioleaching operations.

The impetus to improve the performance of dump bioleach operations and to increase the use of heap bioleaching of copper, in particular, and to some degree heap biooxidation of low-grade sulfidic-refractory gold ore is directly related to exploitation of porphyry and supergene deposits.

Most of the world's largest copper deposits are "porphyry" deposits. These deposits are quintessential low-grade (0.5% copper), large-tonnage deposits, containing hundreds of millions of tonnes of ore and lending themselves to bulk mining practices, which entail taking large volumes of material usually from open-pit operations. Porphyry deposits are located at convergent tectonic plate boundaries in the Canadian Cordillera region, the southwestern United States extending into central Mexico, the Andes Mountains of South America and the Philippines, Indonesia and Papua New Guinea. The occurrence of porphyry deposits is associated with the intrusion of subduction-related magma at shallow levels in the earth's crust, which formed stocks (plutonic rock) with large, well-formed mineral crystals set in a fine-grained host (or country) rock. Copper generally occurs as chalcopyrite in porphyry deposits.

Low-temperature processes that are not related to the primary magmatic-hydrothermal system have made many marginal porphyry deposits economical by further concentrating copper. These "supergene" deposits form from ground water leaching of copper from chalcopyrite and re-depositing the copper as a higher-grade chalcocite (Cu_2S) and bornite (Cu_5FeS_4) below the water table. Supergene deposits are typified (Fig.1) as having a zone of leaching and zone of oxidation above the water table. Below the water table is the zone of secondary enrichment and below this is the primary ore, also referred to as "hypogene ore", which is chalcopyrite (CuFeS_2).

4 Challenges to applying biomining technology

While biomining enjoys considerable success, challenges – both technical and commercial – remain that hinder biomining from achieving its full potential as an applied technology.

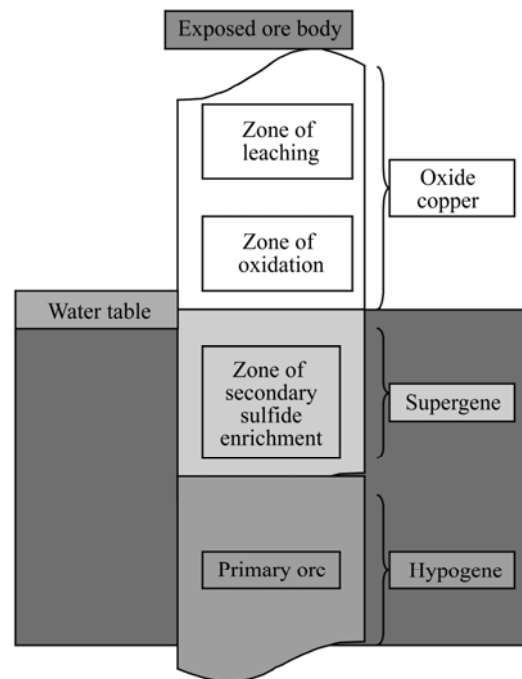


Fig.1 Schematic of supergene ore deposit, showing primary (hypogene) deposit underlying secondary sulfide zone

4.1 Technical challenges

Until recently dump bioleaching has been applied much as it was 50 years ago with minimal research and development aimed at understanding the microbial populations in dumps or how to enhance the performance of dump operations. This inattention was likely the result of low copper prices and that dump bioleaching was an adjunct process to smelting, which was the primary source of revenues for copper operations. The material in many dumps also contained a percentage of chalcopyrite and because of the difficulty of leaching chalcopyrite, it has largely been assumed that the copper associated with chalcopyrite would not effectively leach in dumps. More recently many copper producers have realized that some chalcopyrite is indeed being leached in dumps and with this realization more substantive efforts have been made lately to understand how this occurs and how it can be enhanced.

The discovery of large deposits of low-grade chalcopyrite underlying many of the supergene copper deposits is furthering R&D for both dump and heap bioleaching of chalcopyrite ores. These underlying deposits are typically low-grade and are therefore not always amenable to conventional flotation and smelting practices. These deposits will likely have to be exploited using crushed ore heap bioleaching of the higher-grade materials with adjacent, run-of-mine dump bioleach operations to extract copper from the lower-grade

materials.

Heap bioleaching of chalcopyrite is still in its infancy with the preliminary results of some pilot tests having only recently been presented[8]. Chalcopyrite bioleaching requires elevated temperatures to be successful. The challenges are how to engineer bioleach dumps and heaps to achieve and sustain higher temperatures and how to maintain and control different microbial populations within these massive bioreactors to ensure effective leaching of pyrite to generate heat and to leach chalcopyrite.

Although secondary copper heap bioleaching is widely applied (Table 1), there are still questions and issues with the technology. Many of the secondary copper operations suffer from low temperatures despite the presence of some pyrite, which would be expected to oxidize and subsequently heat the heaps. Are the cool heap temperatures a result of low aeration rates, irrigation procedures, acidification practices, a problem with microbial distribution within the heaps or the nature of the leach chemistry of sulfide minerals? Chalcocite typically leaches quite rapidly in heaps but the leach rate of covellite, a product of chalcocite oxidation, is slow. The slow leach rate of covellite oxidation significantly increases the length of time that the ore must remain on the pad to achieve greater than 85% copper extraction. Can this oxidation rate be increased with technical innovations?

Nickel sulfide heap bioleaching has been piloted at several operations and is currently being demonstrated at large scale at the Talvivaara Mine in Finland[9] with commercial operation expected in late 2008. The challenges of heap bioleaching low-grade, complex, polymetallic ores vary with differing mineralogy. The presence of the mineral pyrrhotite can result in substantial heating of the heap rather quickly and also poses an acid consumption problem. The assemblages of minerals in polymetallic ores leach at different rates and can extend the time required to achieve acceptable metal recoveries. Downstream processing can be challenging and costly with complex mixtures of soluble metals.

Heap biooxidation of coarse, low-grade, sulfidic-refractory gold ores as a pretreatment process has experienced only limited application at commercial scale [5]. Operational aspects to be considered are control of sulfide-sulfur levels, carbonate content, and clays in the ore; ore crush size; avoidance of compaction to maintain good hydraulic conductivity in the ore bed; pad aeration management to ensure adequate air addition without drying of the ore; irrigation management; and maintaining the pad base. High cyanide usage has been reported for some biooxidized ores; this is likely due to

production of partially oxidized sulfur compound that consume cyanide.

Heap biooxidation pretreatment of sulfidic-refractory gold concentrates[10] has also experienced a limited commercial application history. This technology entails agglomerating a flotation concentrate onto coarse ore or inert carrier, heap biooxidizing the sulfides, then separating the oxidized concentrate from the carrier material. The oxidized concentrate is cyanide leached and the carrier can be reused for agglomerating the concentrate. Many of the problems reported for heap biooxidation of sulfidic-refractory gold ores have also been encountered with this technology.

Stirred-tank biooxidation of sulfidic-refractory gold concentrates has been practiced for some 22 years and most problems have been successfully resolved over this period of time. Currently the technology uses injected air. However, the large volumes of gases injected into the tanks under hydrostatic pressure increase power demand. It is likely that using pure oxygen with added CO₂ to decrease the gas volume and diminish power consumption will be used, as stirred-tank sulfidic-refractory gold concentrate plants increase in tonnage throughput. Tank biooxidation operations also report high cyanide consumption for the biooxidized residues. Thermophilic microorganisms may effectively oxidize partially oxidized sulfur compounds that are responsible for increasing cyanide consumption[11]. However, to utilize only thermophilic microorganisms increases both capital and operating costs of these tank biooxidation plants. A combination mesophilic/thermophilic process has been proposed, but has yet to be put into practice.

Bioleaching of chalcopyrite concentrates has been demonstrated using moderately thermophilic bacteria[6] and extremely thermophilic Archaea[12]. Although these demonstrations have been limited in number, bioleaching of chalcopyrite concentrates with moderate thermophiles will likely require finer grinding of the mineral feed to achieve good copper recoveries. Chalcopyrite concentrate bioleaching with the extremely thermophilic Archaea, while successful, requires more exotic materials of construction for the bioreactors to mitigate corrosion, which increases the capital cost. Because the solubility of O₂ is low at the optimum temperature range of the extremely thermophilic Archaea, O₂ enrichment is used; because this lessens the gas volume and it also reduces evaporation rates. While excellent copper recoveries from chalcopyrite concentrate bioleaching at demonstration scale have been reported, stirred-tank bioleaching of chalcopyrite has not become a commercial reality. This may be due to competition from pressure oxidation technology and smelting.

4.2 Commercial challenges

Biomining technology is developed by mining companies, mining biotechnology companies, government laboratories, university scientists and engineers and mining consultants.

Mining companies are motivated to develop biomining technology to process their own minerals deposits, which are not technically and/or economically amenable to conventional technology. Many mining companies patent their biomining technologies or publish details of the technology in the public domain to protect the technology for their own use. Mining companies may or may not make their technology available to other mining companies. Mining companies have a considerable advantage over other organizations and individuals that develop biomining technology, because the mining companies have operations where the innovations can be piloted and demonstrated. Major mining companies also have excellent laboratory facilities and are staffed with scientists and engineers, who can resolve technical problems that inevitably arise during testing, piloting, demonstrating, commissioning and operation. Technologies developed by mining companies are usually developed in response to processing issues at a specific property that is owned and operated by the company.

In response to the mining industry's interest in biomining several biotechnology companies have developed proprietary technologies. These companies broadly patent their technologies and have developed strategies for marketing their innovations. Some companies prefer to license their technologies to mining and/or engineering companies in return for a licensing fee and a NSR royalty. Other mining biotechnology companies have opted to become mining companies themselves and apply their technologies at their own mine sites where applicable. Unless the mining biotechnology company has ready access to a mining property at which the technology can be scaled-up and vetted, the biotechnology company must identify and negotiate with a mining company that is willing to undertake the risk and cost of this effort.

Government laboratories (for example CSIRO in Australia, Mintek in South Africa, Beijing General Research Institute for Nonferrous Metals in China and BRGM in France) contribute highly regarded and significant innovative contributions to biomining. Innovations from government laboratories have entered the commercial realm through collaborations with mining companies and public domain publications. One recent example is the collaboration between Mintek and the NICICO (National Iranian Copper Industries

Company) for pilot testing chalcopyrite heap bioleaching at the Sarcheshmeh Copper Complex[8].

University researchers throughout the world contribute fundamental and applied biomining research. Much of this research is published in technical journals with broad, global readership. Universities and government laboratories are also contracted and funded through AMIRA International, an industry-funded consortium, and BioMinE, a European Union-funded consortium, to provide high-quality biomining technology. Independent consultants and academic researchers, specializing in biomining, transfer technology to the mining industry. Biomining research and development by universities, government laboratories and consultants may, in some cases, be carried out in response to an industrial contract from a mining company. The results are used by the mining entity to help resolve a specific problem or to enhance performance of a particular biomining application.

Several global engineering companies offer mining biotechnology. Some technologies and capabilities have been developed in-house and other innovations have been licensed from biomining technology companies or other sources.

The path to commercial application of biomining technology has challenges; and many of these are common to any new mining technology:

1) Biomining technologies must compete with alternative technologies (pressure oxidation, roasting/smelting and developing chemical leach processes). There are a number of factors that are considered when selecting a technology and biomining may not always meet all of the criteria.

2) New technologies, whether they are biomining or other innovative processes, have a modest chance of being successful. These risks have been detailed by others[13–15]. Failures are costly not only in monetary terms, but also the reputations of mining, engineering and biotechnology companies and individuals are at stake.

3) The time required to bring new biomining technology from the conceptual stage to commercialization is 10–20 a. This necessitates long-term financial, research, development and managerial commitments.

4) New biomining technologies often require a considerable capital investment. For example, the 20 000 t/a BioCOP™ demonstration plant at the Chuquicamata Mine in Chile was estimated at US\$60 million.

5) Biomining technologies, like most hydro-metallurgical processes, are site specific. Therefore, for nearly every biomining technology on-site piloting and large-scale demonstration may need to be conducted for

every application of the technology. One exception is the BIOX™ technology, which has been applied at a sufficient number of locations where an on-site demonstration is typically not necessary, but several months of laboratory piloting must be conducted. On-site pilot trials and demonstration testing are costly and time-consuming. Long-term commitments of time, money, facilities, personnel and management are required by the mining company. Obtaining the commitment of a mining company to undertake such an effort to prove a new process can be onerous for a biotechnology company with limited resources.

6) Patents, which protect the intellectual property of both mining and biomining technology companies and are often essential for the latter to raise financing, can stifle commercial applications of biomining technologies [15]. Mining companies may decide to select an alternative process rather than pay licensing fees and royalties or face litigation in the event of infringement. Efforts may even be made to circumvent intellectual property rights by inventing around the patented process. Another unfortunate consequence of some patents is that technologies become inaccessible when owners of the patents have no interest in marketing the technology or even employing the process they developed and patented.

7) For processes developed by biomining technology companies, process guarantees may need to be offered. Although such guarantees can be formulated for stirred-tank bioleach plants, it is more difficult to devise guarantees for heap leach technologies, because of the number of variables that cannot be adequately monitored or controlled in very large heaps. Process or technology guarantees are relatively futile, because the mine owner “owns” the risk – the mining company has invested heavily in the process, controls the feed to the plant, and is in the command of how the process will be operated [14].

5 Future of biomining

1) While the demand for most metals has steadily increased in the last decade, discoveries have declined [16–17] and those deposits that are being discovered are declining in grade and quality. Processing options for lower grade ore deposits and deposits of lower quality with complex polymetallic mineral assemblages are limited. Biomining technologies are particularly adept at technically and economically processing these types of resources. Mining companies are aware of biomining’s unique niche and chalcopyrite heap bioleaching is already undergoing pilot- and demonstration-scale

testing. There will, of course, continue to be opportunities for the commercial application of stirred-tank biooxidation of sulfidic-refractory gold concentrates, because that technology has been effectively marketed for over two decades and has competed well with pressure oxidation and roasting.

2) Because future biomining applications will likely be directed more on lower-grade, lower-quality, complex ores, it is important that research and development focus on the technical issues associated with these biomining applications. Such studies should address those issues described earlier: understanding how the different temperature groupings of microbes colonize and function within coarse ore heaps; engineering coarse ore and run-of-mine heaps to effectively exploit microbial development and activities including irrigation, aeration and heat management.

3) For biomining technologies to be more widely applied commercially they have to be demonstrated at scale. To achieve this there must be cooperation among the mining companies who own and exploit the deposits, and universities, government laboratories, biotechnology companies and engineering companies that develop the technologies. Organizations such as AMIRA have succeeded to some extent in accomplishing this and this cooperative concept needs to be advanced and exploited.

4) Biomining patents are complicating the commercial development of biomining. Biotechnology companies have a reasonable right to be financially rewarded for their innovations, yet the most costly and most risky part of developing biomining technology is demonstrating the technology at scale and the mining companies assume both the cost and the risk for this. Mining companies, too, have an obligation to protect their rights to use technology that they have developed. However, mining companies are not absolved of blame in the patent morass, because their patents effectively hinder the use of the innovations by other mining companies unless cooperative agreements are made. It is unclear how the situation can and will ultimately be resolved.

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