MINI-REVIEW

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Bioleaching review part B: Progress in bioleaching: applications of microbial processes by the minerals industries

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Abstract This review describes the historical development and current state of metals leaching and sulfide mineral biooxidation by the minerals industries. During the past 20 years commercial processes employing microorganisms for mineral recovery have progressed from rather uncontrolled copper dump leaching to mineral oxidation and leaching in designed bioheaps for oxidation of refractory gold ores and for copper recovery. Also during this period of time, stirred tank bioleaching has been commercialized for cobalt recovery and for biooxidation of refractory gold ores. Chalcopyrite bioleaching in stirred tanks is on the verge of commercialization. Commercial applications of biohydrometallurgy have advanced due to favorable process economics and, in some cases, reduced environmental problems compared to conventional metal recovery processes such as smelting. Process development has included recognition of the importance of aeration of bioheaps, and improvements in stirred tank reactor design and operation. Concurrently, knowledge of the key microorganisms involved in these processes has advanced, aided by advances in molecular biology to characterize microbial populations.

Introduction and historical perspective

Application of microbial processes by the mineral industry—biohydrometallurgy—predates the understanding of the role of microorganisms in metals extraction, commonly referred to as bioleaching. Copper recovery from mine waters can be dated to the fifteenth or sixteenth centuries. Paracelsus (1493–1541) described the process as follows: “For truly when the rustics in Hungary cast iron at the proper season into a certain fountain, commonly called Zifferbrunnen, it is consumed into rust and when this is liquefied with a blast-fire, it soon exists as pure Venus (copper), and nevermore returns to iron. Similarly in the mountain commonly called Kutenberg they obtain a lixivium out of marcasites, in which iron is forthwith turned into Venus of high grade, and more malleable than the other produced by nature” (Davidson 1982). Undoubtedly, microbial processes were at work to leach the copper from sulfide minerals, which the rustics were able to recover by the process now known as precipitation on iron.

Biooxidation of sulfide ores for copper recovery has been practiced for centuries in Spain, Sweden, Germany, China and elsewhere by solution mining techniques (Ehrlich 1999). An early documented commercial application of a biohydrometallurgy process in the mining industry was for copper extraction from mine waste (Zimmerley et al. 1958). The acidophilic iron oxidizing Thiobacillus ferrooxidans was recognized as a means to maintain iron in the oxidized ferric form to serve as the oxidant for sulfide copper minerals in order to solubilize copper. The run-of-mine material of low grade copper, stacked in waste dumps to depths over 100 m in height was leached using an acidic ferric iron solution for economic recovery of copper at the Kennecott Bingham Mine near Salt Lake City, Utah. Although the role of the iron oxidizing bacteria was recognized, the mine dump, as a reactor, was not designed to promote the activity of the bacteria.

Harrison et al. (1966) reported the role of the iron oxidizing Acidithiobacillus ferrooxidans in leaching of uranium. The uranium ore was stacked in heaps, similar to dump leaching of low-grade copper ore, and leached using an acidic ferric sulfate solution at the Elliot Lake Mine, Ontario, Canada. The presence of the bacteria in the heaps was discovered and their role in maintaining oxidizing conditions by conversion of ferrous to ferric iron for extraction of the uranium defined. A unique commercial application for extraction of uranium from
underground low-grade ore was demonstrated at the Denison Mine, Ontario, Canada (McCready and Gould 1990). A system for intermittent flooding of blasted ore in an underground stope, sealed with a concrete wall, demonstrated the utility for a hydrometallurgical process for uranium extraction. This process also considered the important requirements of the microorganisms for optimal activity in the process. Nutrients and aeration were provided to promote bacterial growth. However, the economics of uranium have precluded further use and advancement in development of microbial processes for extraction of uranium.

Commercial application of biohydrometallurgy, designed to facilitate the activity of the microorganisms, was initiated in 1980 for copper leaching from heaps. The Lo Aguirre mine in Chile processed about 16,000 t ore/day between 1980 and 1996 using bioleaching (Bustos et al. 1993). Numerous copper heap bioleach operations have been commissioned since 1980 (Brierley and Brierley 1999).

Another successful and extensive commercial application of biohydrometallurgy is biooxidation pretreatment of refractory sulfidic gold ores. For this process, the microorganisms are used to oxidize pyrites, arsenopyrites or arsenopyrites to expose gold occluded within the sulfide minerals matrix. Following biooxidation pretreatment, the gold is extracted and recovered by conventional hydrometallurgical processes such as cyanide leaching and recovery on carbon or precipitation on zinc. The biooxidation pretreatment plant with the longest history of operation is Goldfields’ (previously Genmin) BIOX process at the Fairview Mine in South Africa. This plant, operating since 1986, treats refractory arsenopyrites/pyrite gold-bearing concentrate in large, stirred-tank, aerated, continuous-flow reactors (Marais 1990; van Aswegen et al. 1991). All commercial plants using the BIOX, or similar aerated stirred-tank processes, treat concentrates prepared from the ores to enrich the gold and sulfide content, and one also leaches cobalt from sulfidic tailings. One commercial plant treats refractory gold ore in heaps. Newman Mining Corporation employs the biooxidation-heap process for pretreatment of refractory gold ore followed by conventional milling in a cyanide-CIP circuit for gold recovery at its Gold Quarry Mine, Elko, Nevada (Brierley 2000). Biooxidation is carried out on crushed ore stacked on pads with an air-ventilation system at the base to supply oxygen to the microbial population inoculated on the rock. After 100–270 days biooxidation pretreatment to degrade the sulfide mineral matrix, the ore is removed and processed through a conventional mill to extract the gold.

**Microbial systems used for bioleaching**

Mesophilic microorganisms

Following the discovery that microorganisms played a role in production of acid mine drainage (Colmer and Hinkle 1947), the first acidophilic iron- and sulfur-oxidizing bacterium, *T. ferrooxidans*, was isolated and described (Temple and Colmer 1951). It was not long before the microbial role in oxidation of sulfide minerals was investigated from an extractive metallurgy perspective. Microorganisms cultured from leach streams in waste rock dumps at the Bingham Canyon, Utah mine oxidized pyrite (FeS₂) and copper minerals and released copper into solution (Bryner et al. 1954). *T. ferrooxidans* was used in numerous early investigations into bioleaching of sulfide minerals, for it was the only known acidophilic iron-oxidizing bacterium until the description of *Leptospirillum ferrooxidans* (Markosyan 1972). Recently, *Thiobacillus thiooxidans*, and *Thiobacillus caldus*, as well as *T. ferrooxidans* were reassigned to the new genus *Acidithiobacillus* (Kelly and Wood 2000).

The important role of iron-oxidizing *L. ferrooxidans* in metal sulfide biooxidation was slow to be recognized. It is not as easily enriched as *A. ferrooxidans* from samples containing both organisms, growing more slowly than *A. ferrooxidans* in typical ferrous iron-rich media. Nor is it easy to compare relative numbers of these two organisms in liquid or solid samples using conventional culturing techniques.

An early indication of the importance of *L. ferrooxidans* in bioleaching was that a mixed culture of *L. ferrooxidans* and *A. thiooxidans* could oxidize pyrite faster than *A. ferrooxidans* (Norris and Kelly 1978). The propensity of *L. ferrooxidans* to attach to sulfide minerals, its high affinity for ferrous iron (Kₐ 0.25 mM compared to 1.34 mM in *A. ferrooxidans*), and its low sensitivity to inhibition by ferric iron (Kᵢ 42.8 mM compared to 3.10 mM in *A. ferrooxidans*) (Norris et al. 1988) was additional evidence of the importance of *L. ferrooxidans* in bioleaching. Evaluations of field samples and laboratory ore percolation studies led to the conclusion that *L. ferrooxidans* could be as significant as *A. ferrooxidans* in bioleaching (Sand et al. 1992).

Molecular biology techniques showed that *Leptospirillum* was the dominant iron-oxidizing bacterium in continuous stirred tank reactors (CSTRs) where gold-bearing arsenopyrite (FeAsS) and copper-containing concentrates were biooxidized at 40°C and pH 1.6 (Rawlings 1995; Rawlings et al. 1999). Similarly, immunofluorescence analysis of the primary stage tanks of commercial biooxidation plants at Sao Bento, Brazil, and Fairview, South Africa indicated the numerical dominance of *Leptospirillum over A. ferrooxidans* (Dew et al. 1997).

The dominance of *Leptospirillum* species over *A. ferrooxidans* also occurs in column bioleaching of copper sulfides (De Wulf-Durand et al. 1997; Vazquez and Espejo 1997). Pizarro et al. (1996), using DNA analysis, showed that the dominant iron-oxidizing bacteria varied depending on whether ferrous iron was added to leach solutions applied to columns containing copper sulfide ore. In the absence of added iron, *L. ferrooxidans* was dominant and *A. ferrooxidans* was not detected. However, when ferrous iron was added *A. ferrooxidans* was
dominant. Similarly, addition of ferrous iron to leach solutions resulted in growth of predominantly \textit{A. ferroxidans}.

Detailed molecular analyses indicate there are at least two major groups of leptospirilla, though there are no marked physiological or physical differences between them (Coram and Rawlings 2002). One of these groups (Group II) has been proposed as a new species, \textit{Leptospirillum ferriphilum}. Several isolates that are members of Group II are able to grow at 45°C. None of the Group I members grows at 45°C. Isolates from commercial biooxidation tanks at the Fairview Mine were all Group II members. A proposed third group of \textit{Leptospirillum} was indicated by molecular analyses of slimes in extreme acid mine drainage at Iron Mountain, California (Bond et al. 2000). These organisms have not been obtained in pure culture.

Also detected in the very low pH, high dissolved solids environment at Iron Mountain were large numbers of the recently described genus \textit{Ferroplasma} (Edwards et al. 2000), an iron-oxidizing archaeon originally described in a biooxidation pilot plant (Golyshina et al. 2000). Although little bioleaching work has been done with \textit{Ferroplasma} sp., it may be an important component of bioleaching microflora under certain conditions. In this connection, a \textit{Ferroplasma} sp. was the dominant organism cultured from the second and third reactors in a three-reactor train in which a polymetallic sulfide (chalcopyrite, sphalerite, pyrite) was continuously biooxidized at 45°C (Okibe et al. 2003). Its dominance was attributed to the increasingly acidic, high dissolved solids conditions as the mineral slurry passed through the train of reactors. Higher organic carbon in the latter reactors also may have favored its growth. The study, conducted at the putative boundary of mesophilic and moderately thermophilic conditions (45°C), also showed \textit{Acidithiobacillus caldus} as the dominant sulfur oxidizer. \textit{Leptospirillum} was the dominant iron oxidizer in the first reactor; an extremely acidophilic, moderately thermophilic strain was isolated.

Thermophilic microorganisms

Exothermic biooxidation of sulfide minerals produces significant heating in stirred tank reactors and in heaps. The connection between microbial activity and heat production in copper sulfide ore heaps and dumps (Murr and Brierley 1978) suggested the importance of thermophiles in bioheap leaching. Use of thermophiles was found to improve metal sulfide biooxidation in at least two ways (Brierley and Brierley 1978). First, reaction rates increased with increasing temperature. Second, elevated temperature increased the extent of metal extraction from certain minerals, most notably bioleaching of copper from chalcopyrite (CuFeS\textsubscript{2}). Chalcopyrite is the most important ore of copper and is not successfully bioleached with mesophiles due to passivation after only partial copper extraction. There is considerable interest today in applying thermophiles to bioleach chalcopyrite in stirred tank reactors and in bioheap leaching.

Moderately thermophilic iron- and sulfur-oxidizing bacteria were initially cultured from mining environments (Brierley 1978) and hot springs (Brierley et al. 1978). Development of moderate thermophiles in self-heating heaps of sulfide ores continues to be observed in recent mining operations including heaps of refractory gold ore undergoing biooxidation (Brierley 1997a, 1997b) and in copper sulfide heap leaching (Ream and Schlitt 1997). A moderately thermophilic mixed culture was applied commercially for the tank biooxidation of refractory sulfidic gold ore concentrates at the Youanmi plant in Australia (Miller 1997). In addition to possibly improving sulfide oxidation with higher temperature, operation of stirred reactors at 50°C reduces process-cooling requirements.

The discovery of unusual, extremely thermophilic microorganisms in acidic, sulfidic hot springs led to evaluations of these microorganisms for their ability to oxidize “difficult” minerals such as chalcopyrite and molybdenite (MoS\textsubscript{2}) (Brierley and Murr 1973; Brierley 1977; Brierley and Brierley 1978). Now known as archaebacteria, these organisms, together with strains of extreme thermophiles discovered more recently, have expanded bioprocessing options in terms of temperature and metal tolerance. Stirred tank bioleaching of chalcopyrite concentrates with extreme thermophiles has been tested at pilot scale, and a plant with annual production of 20,000 t copper is planned (Craven and Morales 2000).

Bioleaching processes involve consortia of microorganisms

The complete biooxidation of sulfide minerals involves biooxidation of both iron and sulfur. Iron-oxidizing microorganisms produce ferric ions. Ferric oxidation of certain metal sulfides (e.g., pyrite), yields thiosulfate, which is oxidized to sulfuric acid biologically and/or chemically. In other cases, such as with chalcopyrite, arsenopyrite, or sphalerite (ZnS), elemental sulfur is produced, via polysulfide intermediates (Schippers and Sand 1997). Consequently, sulfur-oxidizing microorganisms such as \textit{A. thiooxidans} and \textit{A. caldus} are significant components of the microflora in commercial bioleaching operations. Sulfur-oxidizing microorganisms reduce the accumulation of sulfur and may improve bioleaching efficiency of sphalerite and arsenopyrite (Dopson and Lindstrom 1999; Fowler and Crundwell 1999). \textit{A. caldus} is the dominant sulfur oxidizer over \textit{A. thiooxidans} in pilot plants where biooxidation of arsenopyrite or copper concentrates occurs at 40°C (Rawlings et al. 1999) to 45°C (Okibe et al. 2003).

Mineral feeds to heap and tank biooxidation processes typically contain indigenous iron- and sulfur-oxidizing mesophilic and thermophilic microorganisms. Even in situations where a mineral biooxidation process is started with a specific inoculum of iron- and sulfur-oxidizing
Microorganisms, selection will occur for organisms most suited to grow under a given set of conditions. An example of this phenomenon is the growth of thermophiles in dump and heap leaching operations as temperatures increase from exothermic biooxidation of sulfides by mesophilic organisms.

Conditions for growth of microbes in commercial bioleaching operations

Microorganisms that biooxidize sulfide minerals at low pH are resistant to acidic conditions and most heavy metals in process solutions. Typically, microbial cultures are pre-grown or adapted to a particular ore feed in the laboratory or pilot plant. In this manner, potentially inhibitory agents in the feed select for organisms able to oxidize iron and sulfur in the presence of the agents. For example, the tolerance to arsenic has been increased under selective pressure in CSTRs. Mercuric ions select for strains that volatilize mercury by mercuric reductase (Olson et al. 1982).

However, their unique physiology makes acidophiles sensitive to inhibition by organic acids and certain anions. Acidophiles maintain an intracellular pH near neutrality. As a consequence, the proton gradient between the environment and the cytoplasm may be 4 or 5 orders of magnitude. This gradient is maintained, at least in part, by an inside-positive membrane potential (Ingledew 1990; Matin 1999). While this potential helps to exclude protons, it renders the cell sensitive to lipophilic anions, such as thiocyanate and, to a lesser extent, nitrate. These ions cross the cytoplasmic membrane and accumulate in response to the membrane potential. This accumulation inhibits cells in two ways: (1) increased proton uptake and resultant acidification of the cytoplasm, and (2) anions may react with cell constituents, such as binding to active sites of enzymes. The latter appears to be the case with thiocyanate and bisulfite ions.

Many organic acids are protonated at low pH and hence are membrane permeable. Inside the neutral pH cytoplasm, the molecule dissociates, releasing protons and acidifying the cell. This mechanism applies also to fluoride, which occurs predominantly as HF below pH 3.2 (Suzuki et al. 1999).

These sensitivities require attention to chemistry of process solutions. For example, thiocyanate is produced by reaction of cyanide with reduced sulfur species during cyanidation of biooxidized gold ore concentrates. Process solutions containing thiocyanate that became mixed with biooxidation solutions have caused problems at biooxidation plants (Miller 1997). Second, the supply of water for biooxidation processes at a mine must be evaluated for potentially inhibitory agents. For example, water high in chloride (more than a few grams per liter) inhibits metal sulfide biooxidation. Consequently, a saline water supply or the presence of soluble Cl-containing minerals in ore may restrict biooxidation options.

Temperatures are controlled in CSTR biooxidation plants. The high rates of exothermic metal sulfide oxidation require cooling of commercial reactors. Cooling requirements are lessened by operating in the moderate thermophile temperature range, as at the Youanmi plant (Miller 1997).

Exothermic oxidation of sulfides also causes heating in bioheaps. For example, Newmont Mining Company’s commercial biooxidation operation in Nevada has measured temperatures up to 81°C in heaps containing 1.4–1.8% sulfide-sulfur (Tempel 2003). Temperatures as high as 66°C were noted in a 960,000 t test heap of low grade, run of mine chalcopyrite ore containing 4% pyrite at Kennecott Utah Copper (Ream and Schlitt 1997). Heaps heat as mesophilic microorganisms grow and oxidize sulfides. As temperatures increase to >40°C, mesophiles are displaced by moderately thermophilic iron- and sulfur-oxidizers (Murr and Brierley 1978). Extreme thermophiles may displace moderate thermophiles where temperatures increase to above 60°C. Although moderate thermophiles are cultured from hot heaps (Brierley 1997a; Ream and Schlitt 1997), extremely thermophilic archaea are much less commonly detected. However, large populations of extremely thermophilic archaea can be maintained in heaps inoculated with these organisms (Tempel 2003).

Controlling the temperature in heaps is difficult. However, this being explored, especially in connection with bioheap leaching of chalcocite, which is more successful with thermophiles. Heap height is an important factor in the temperature rise, which increases with the square of heap height (Ritchie 1997). Other factors important in heap heating include sulfide oxidation rate, aeration and irrigation rates, and the local climate (Dixon 2000).

High volumes of air must be supplied in CSTR sulfide biooxidation processes. Efficient delivery of oxygen is the single largest operating cost in refractory gold biooxidation plants. The volume of air that must be supplied is based on the sulfide oxidation required. For example, at Wiluna in Western Australia, about 8 t air was supplied per tonne of concentrate, at typical oxygen utilization efficiencies of 25% (Brierley and Briggs 2002).

Aeration of bioheaps can accelerate biooxidation reactions, reducing leach cycle time. Air may be delivered via a network of pipes installed in a gravel layer at the base of heaps. Air distribution networks typically include 500 mm headers and 50 mm diameter laterals at 2 m spacing. Holes are drilled in the bottom of the 50 mm diameter air distribution pipes. The density of holes is dependent on the amount of sulfide-sulfur to be oxidized and the oxidation rate. Air is injected into the heap using a set of low-pressure high volume fans or blowers (Brierley and Briggs 2002).
Microbial processes for metals leaching and mineral biooxidation

The processes by which microorganisms facilitate mineral biooxidation and bioleaching are termed "contact" and "non-contact" mechanisms. Rohwerder et al. (2003) describe these mechanisms in detail.

Iron plays a key role in metal sulfide biooxidation processes. The ferrous-ferric ratio has a dominating effect on the solution redox potential in biooxidation systems. It is the iron-oxidizing microorganisms, mesophilic or thermophilic, that increase the redox potential resulting in metal sulfide biooxidation. The presence of ferric ions alone is not sufficient for biooxidation of a metal sulfide if the redox potential is not sufficiently oxidizing. Attached microorganisms may facilitate the process by localization of ferric ions in the exopolymeric material at the mineral surface (Sand and Gehrke 1999).

Sulfide minerals vary in susceptibility to biooxidation. The electrochemical potential of sulfide minerals is the fundamental basis of dissolution and is related to differences in metal-sulfur bond energies in lattice structures (Riekkola-Vanhanen and Heimala 1993). In a system containing a mixture of metal sulfides, the mineral with the lowest potential tends to oxidize first, sometimes to an appreciable extent before minerals with higher potentials. Sulfides like sphalerite (ZnS) or pyrrhotite (FeS) have low electrode potentials of approximately 100 mV to 300 mV versus standard hydrogen electrode (Riekkola-Vanhanen and Heimala 1993) and are readily biooxidized. In contrast, molybdenite (MoS2) has a rest potential of about 700 mV and is difficult to bioleach (Romano et al. 2001). Similarly, enargite (Cu3AsS4) resists bioleaching (Olson and Clark 2001).

The formation of refractory surface layers may slow metal sulfide biooxidation. Although sphalerite is easily leached, a product layer of elemental sulfur, forming under low redox conditions, needs to be removed by microbial sulfur oxidation before sphalerite can be effectively leached (Fowler and Crundwell 1999). Chalcopyrite often exhibits parabolic bioleaching kinetics due to formation of a refractory surface layer. There is disagreement as to the nature of this passivating layer. Extreme fine grading and use of thermophiles can overcome this problem.

Pyrite plays a key role in many biooxidation operations. Its oxidation produces acidic, heat and dissolved iron. Pyrites vary greatly in their chemical and biological reactivity (Baldi et al. 1992). It appears that imperfections in crystal structure contribute to ease of oxidation. Highly crystalline pyrite resists oxidation whereas frambooidal pyrite oxidizes more easily.

Non-sulfide minerals occurring with the sulfide ore significantly affect growth and activity of metal sulfide-oxidizing microorganisms. For example, if the carbonate content of an ore exceeds its acid producing potential, the organisms may not be able to maintain the acidic conditions required for their growth. This is less a problem in stirred tank reactor biooxidation processes in which ores go through a preliminary concentration step to increase the grade of metal sulfides and remove gangue minerals.

Also problematic in bioheap leaching is the presence of excessive fines, especially clay minerals. These may migrate with leach solution to the bottom of a heap and restrict water flow and access of oxygen.

Bioleaching of base metals

There are 11 full-scale, stirred-tank bioleaching plants employing three different technologies to process sulfidic-refractory precious metal concentrates and concentrates of pyrite, cobalt and chalcopyrite (Brierley and Briggs 2002). Bioheap leaching for recovery of copper has now become a common practice in the industry. Since 1980 at least 13 copper bioleach operations have been commissioned (Table 1), but not all are currently in production because of depletion of ore reserves or, in one case, problems in operation.

The copper bioleach plants listed in Table 1 are for recovery of copper from the mineral chalcocite (Cu2S). Copper is leached from chalcocite by acid (Eq. 1), forming covellite (CuS), or by ferric iron formed from microbial oxidation of ferrous iron (Eq. 2).

\[
2CuS + 2H_2SO_4 + O_2 \rightarrow 2CuS + 2CuSO_4 + 2H_2O \quad (1)
\]

\[
Cu_2S + Fe_2(SO_4)_3 \rightarrow 2CuSO_4 + 2FeSO_4 + S \quad (2)
\]

The mineral covellite is subsequently also leached by ferric iron (Eq. 3). Chalcopyrite leaching

\[
CuS + Fe_2(SO_4)_3 \rightarrow CuSO_4 + 2FeSO_4 + S \quad (3)
\]

generally considered a two-step process (Eqs. 1, 3).

Copper in the form of the mineral chalcopyrite (CuFeS2) leached poorly in conditions designed for recovery from chalcocite. New technologies are now being developed using thermophilic microorganisms for bioleaching copper from chalcopyrite, using either heap or stirred-tank reactor systems.

Table 1 Commercial copper bioheap leach plants

<table>
<thead>
<tr>
<th>Plant and location</th>
<th>Size: tonnes ore/day</th>
<th>Years in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lo Aquirre, Chile</td>
<td>16,000</td>
<td>1980–1996</td>
</tr>
<tr>
<td>Gunpowder’s Mammoth Mine,</td>
<td>In-situ*</td>
<td>1991–present</td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mt. Leyson, Australia</td>
<td>1,370</td>
<td>1992–1997</td>
</tr>
<tr>
<td>Cerro Colorado, Chile</td>
<td>16,000</td>
<td>1993–present</td>
</tr>
<tr>
<td>Girahmone, Australia</td>
<td>2,000</td>
<td>1993–in closure</td>
</tr>
<tr>
<td>Ivan-Zar, Chile</td>
<td>1,500</td>
<td>1994–present</td>
</tr>
<tr>
<td>Quebrada Blanca, Chile</td>
<td>17,300</td>
<td>1994–present</td>
</tr>
<tr>
<td>Andacollo, Chile</td>
<td>10,000</td>
<td>1996–present</td>
</tr>
<tr>
<td>Dos Amigos, Chile</td>
<td>3,000</td>
<td>1996–present</td>
</tr>
<tr>
<td>Cerro Verde, Peru</td>
<td>32,000</td>
<td>1996–present</td>
</tr>
<tr>
<td>Zaldivar, Chile</td>
<td>~20,000</td>
<td>1998–present</td>
</tr>
<tr>
<td>S&amp;K Copper, Myanmar</td>
<td>18,000</td>
<td>1998–present</td>
</tr>
<tr>
<td>Equatorial Tonopah, USA</td>
<td>24,500</td>
<td>2000–2001</td>
</tr>
</tbody>
</table>

* ~1.2 million t ore body
Bioheap leaching of chalcocite is performed on ore crushed to particle sizes that may range between about 1 cm and 4 cm, depending on results of a cost benefit analysis that takes into account copper bioleaching rate, recovery, crushing costs, pad area and other economic factors. Crushed ore is agglomerated and stacked to a height of 6–10 m in heaps that may be hundreds of meters in length and width. Leach solution is applied generally by drip irrigation. Pregnant leach solution draining from heaps is enriched in copper sulfate and is sent to a solvent extraction-electrowinning circuit for copper recovery. Copper production ranges from about 10,000 t Cu/year in smaller operations to over 100,000 t/year in larger operations at a cash cost ranging from US $0.40 to US $0.65 per pound of Cu (Brierley and Brierley 2000).

To date, there are no commercial scale bioleach operations for recovery of zinc or nickel. Bench scale studies, and in some cases pilot plant tests, have indicated potential for extension of bioleach technology to other metals.

### Biooxidation pretreatment of precious metal ores

The first commercial, stirred-tank bioleach plant was commissioned in 1986 to pretreat a sulfidic gold concentrate to enhance gold recovery (Brierley and Briggs 2002). Table 2 lists the commercial stirred-tank bioleach plants for pretreatment of refractory gold concentrates. The largest of these operations is Sansu, where nearly 1,000 t concentrate are processed daily in reactors up to 900 m³ in size.

Typically, refractory gold plants operate with a 15–20% slurry density. The slurry is fed continuously to a primary reactor. Most of the microbial growth occurs in the primary reactor, which has a typical slurry residence time of 2–2.5 days. The primary reactor overflows to a series of smaller secondary reactors connected in series. This design increases the efficiency of sulfide oxidation by reducing short-circuiting of sulfide particles. Total residence time in the circuit is about 4–6 days (Brierley and Briggs 2002). The optimum design of a bioleaching plant, including size and number of reactors, has been discussed (Crundwell 2001).

In December 1999, Newmont Mining Corporation commissioned the first biooxidation heap facility for pretreatment of refractory gold ore (Tempel 2003). Biooxidation pretreatment of P80 19 mm ore stacked with haul trucks in pads each 305 m ×147 m ×12.8 m is conducted over a period of 150 days to oxidize 40–45% of the sulfide-S content of the ore. The sulfides occur as pyrite and arsenianpyrite occluding the gold. Following biooxidation, the oxidized ore is removed from the heap and processed by milling and carbon-in-leach for cyanide recovery of the gold.

Gold recovery was 30–39% before biooxidation, increasing to 49–61% after biooxidation. Gold recovery was less than the targeted 71% due to construction and process changes necessitated by declining gold prices. Original design criteria were for smaller ore particle size (P80 10 mm), longer biooxidation time (270 days), and ore stacking with radial stackers that would lessen heap compaction from haul trucks.

The plant uses a mix of microorganisms including mesophilic *A. ferrooxidans*, *L. ferrooxidans*, moderately thermophilic *Sulfobacillus* species and thermophilic archaea *Acidianus* and *Metallospheara* species. A mix is required as pyrite oxidation increases areas within the heap to temperatures as high as 81°C, necessitating the use of thermophilic archaea as well as the mesophilic bacteria (Brierley 2001). The microbe mix is inoculated on the ore prior to stacking in the heap in order to provide uniform distribution of an active mix of the culture throughout the heap (Brierley 1994).

Brierley and Briggs (2002) have published a comprehensive description of the equipment and processes used for commercial biooxidation.

<table>
<thead>
<tr>
<th>Plant and location</th>
<th>Size (tonnes concentrate/day)</th>
<th>Technology</th>
<th>Years in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairview, South Africa</td>
<td>Initially 10 Expanded to 35 Expanded to 40</td>
<td>BIOX</td>
<td>1986–present</td>
</tr>
<tr>
<td>Sao Bento, Brazil</td>
<td>Initially 150 Expanded</td>
<td>BIOX Eldorado</td>
<td>1990–present</td>
</tr>
<tr>
<td>Wiluna, Australia</td>
<td>Initially 115 Expanded to 158</td>
<td>BIOX</td>
<td>1993–present</td>
</tr>
<tr>
<td>Sansu, Ghana</td>
<td>Initially 720 Expanded to 960</td>
<td>BIOX</td>
<td>1994–present</td>
</tr>
<tr>
<td>Youanmi, Australia</td>
<td>120</td>
<td>BacTech</td>
<td>1994–1998</td>
</tr>
<tr>
<td>Tamborague, Peru</td>
<td>60</td>
<td>BIOX</td>
<td>1990–present</td>
</tr>
<tr>
<td>Beaconsfield, Australia</td>
<td>~70</td>
<td>BacTech</td>
<td>2000–present</td>
</tr>
<tr>
<td>Laizhou, China</td>
<td>~100</td>
<td>BacTech</td>
<td>2001–present</td>
</tr>
</tbody>
</table>
Future developments

“Much of the future of biomining is likely to be hot” (Rawlings 2002). Use of moderately thermophilic bacteria and thermophilic archaee is gaining significant attention for commercial applications. Billiton Process Research (Dew et al. 2000) report benefits of moderate thermophiles for bioleaching of nickel concentrates. Pilot scale test work shows extreme thermophiles achieve efficient bioleaching of primary copper sulfate and nickel sulfide concentrates, giving higher recoveries than achieved by bioleaching with either mesophilic or moderate thermophilic cultures. BHP-Billiton is actively developing proprietary technologies for stirred-tank bioleach of chalcopryte concentrates (Craven and Morales 2000). BacTech/Mintek with Industrias Penoles of Mexico recently operated a stirred-tank bioleach pilot plant (170 m³ capacity) in Monterrey, Mexico using moderately thermophilic microorganisms (van Staden et al. 2003). The project focused on a polymetallic (chalcopyrite, sphalerite, galena) concentrate containing precious metals. Recoveries of 96–97% Cu, 99% Zn, 98–99% Au and 40% Ag were achieved at a feed rate of 2.7 t/day. Stable closed-circuit operation was maintained and 0.5 t/day of high purity copper cathode was produced. Bioleaching of “dirty” concentrates, with their high smelter penalty costs, represents some of the most attractive new applications for stirred reactor bioleaching. In addition to stirred reactors, bioleaching of copper from chalcopryte ore in heaps using thermophiles will likely become a reality within the next few years.

The GEOCOAT process, developed by Geobiotics, Lakewood, Colorado, is a unique heap leach system for biooxidation pretreatment of refractory precious metal concentrates and bioleaching copper, zinc or nickel sulfide concentrates. Concentrates or finely ground ore are agglomerated onto coarse ore particles or inert substrates. The coated particles then bioleach in a heap configuration (Whitlock 1997; Johansson et al. 1999).

A committee of the United States National Research Council (2002) states “...the application of biotechnology to the extraction and recovery of metals, is becoming an increasingly important hydrometallurgical processing tool.” The mining industries also recognize that biotechnology offers another tool for economic recovery of metal values. Future developments will expand the role of biotechnology in the extraction and recovery of many metal values.

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