Biomineralization of metal-containing ores and concentrates

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Biomining is the use of microorganisms to extract metals from sulfide and/or iron-containing ores and mineral concentrates. The iron and sulfide is microbiologically oxidized to produce ferric iron and sulfuric acid, and these chemicals convert the insoluble sulfides of metals such as copper, nickel and zinc to soluble metal sulfates that can be readily recovered from solution. Although gold is inert to microbial action, microbes can be used to recover gold from certain types of minerals because as they oxidize the ore, they open its structure, thereby allowing gold-solubilizing chemicals such as cyanide to penetrate the mineral. Here, we review a strongly growing microbially-based metal extraction industry, which uses either rapid stirred-tank or slower irrigation technology to recover metals from an increasing range of minerals using a diversity of microbes that grow at a variety of temperatures.

Microorganisms have been active in the formation and decomposition of minerals in the earth’s crust since soon after life on earth began. Our ability to harness the natural capability of certain microbes to decompose a variety of mineral deposits is an old process that dates back to Roman times in the first century BC, and probably the Phoenicians before that. These early miners used microbial activity to leach copper from ore without being aware that microbes were involved. Although some microbe-assisted metal recovery has been practiced for centuries, in recent years there has been a strongly growing minerals biotechnology industry [1,2]. There are several reasons for this [3].

As high-grade surface mineral deposits are worked out, the traditional pyrometallurgy-based metal recovery processes have become less economically viable, and mining companies have been required to find new processes to work the remaining lower-grade deposits. Microbe-based processes have clear economic advantages in the extraction of metals from many low-grade deposits. For example, large quantities of copper have been recovered from low-grade ores and dumps that have been left behind from previous mining operations by using the biological activity that takes place during controlled irrigation of the dump. Microbial metal-extraction processes are usually more environmentally friendly than physical–chemical processes. They do not use the large amounts of energy required by roasting or smelting and do not produce sulfur dioxide and other harmful gaseous emissions. In addition, mine tailings (residues) and wastes produced from physicochemical processes might be biologically leached when exposed to rain and air, producing unwanted acid and metal pollution. Tailings from biomining operations are less chemically active and the biological activity they can support is reduced by the extent to which they have already been bioleached.

Mineral-degrading microorganisms

The most important mineral-decomposing microbes are the iron- and sulfur-oxidizing chemolithotrophs, which grow autotrophically by fixing CO₂ from the atmosphere. Not all of the mineral-oxidizing organisms are equally efficient at CO₂ fixation, and some grow better when provided with air that has been enriched with 0.5–5.0% (v/v) carbon dioxide [4,5]. Unlike most autotrophic organisms that use radiant energy from sunlight, chemolithotrophs obtain their energy by using either ferrous iron or reduced inorganic sulfur compounds (some use both) as an electron donor, and oxygen as the electron acceptor. As sulfuric acid is produced during the oxidation of inorganic sulfur, these organisms grow in low-pH environments. Most mineral bio-oxidation processes operate at a pH between 1.4 and 1.6. At low pH, ferric iron is soluble and many of the sulfur-oxidizing organisms are able to use ferric iron in place of oxygen as an electron acceptor. This ability is relevant in non aerated heap reactors in which oxygen might not penetrate to the bottom of the heap. The modest nutritional requirements of these organisms are provided for by the aeration of an iron- and/or sulfur-containing mineral suspension in water or the irrigation of a heap. Small quantities of inorganic fertilizer can be added to ensure that nitrogen, phosphate, potassium and trace element limitation does not occur. As might be expected, microbes that grow in mineral-rich environments are, in most cases, remarkably tolerant to a wide range of metal ions [6].

In mineral biooxidation processes that operate at 40 °C or less, the most important microorganisms are believed to be a consortium of Gram-negative bacteria. These include the iron- and sulfur-oxidizing Acidithiobacillus ferrooxidans (previously Thiobacillus ferrooxidans), the sulfur-oxidizing At. thiooxidans (previously T. thiooxidans), At. caldus (previously T. caldus), and the iron-oxidizing Leptospirillum ferrooxidans and L. ferrihophilum [7–11]. In stirred-tank processes, the steady state ferric iron
concentration is usually high, and under such conditions
At. ferrooxidans appears to be less important than a
combination of Leptospirillum and At. thiooxidans or At.
caldus [12]. Studies on microorganisms that dominate
bioleaching consortia at temperatures of 50 °C, have been
less well reported. However, these are believed to include
At. caldus, some Leptospirillum spp., bacteria belonging to
the Gram-positive genera Sulfolabacillus and Acidimicro-
bium [4], and frequently members of the archaeal genus,
Ferroplasma [13]. The types of microorganisms found in
heap-leaching processes are similar to those found in
stirred-tank processes, with At. ferrooxidans, At. thioox-
idans and L. ferrooxidans being most frequently detected
[14,15]. However, the proportions of these bacteria can
vary depending on the conditions under which the heap is
operated [16]. At temperatures > 70 °C, biomining con-
sortia are dominated by archaea rather than by bacteria,
with species of Sulfolobus and Metallosphaera being most
prominent [17].

**Strategies for metal recovery**

Sulfides of metals such as zinc, copper, nickel, cobalt are
almost insoluble in water, but the sulfates of these metals
are readily soluble. When the metal sulfide is oxidized to
its sulfate, the metal is leached into solution from where it
can be extracted. Current understanding of the mechan-
ism of metal solubilization is that it is primarily a chemical
process, although attachment of microbes to the mineral
can enhance dissolution [18,19]. Depending on the
mineral, chemical attack is by a combination of ferric
iron and acid (protons), whereas the role of the microor-
ganisms is to generate the ferric iron and acid. This
strategy for metal recovery is known as bioleaching
because the metal is solubilized in the process.

A second strategy applies mainly to the recovery of gold
from difficult-to-treat (recalcitrant) arsenopyrite ores and
concentrates. Gold is inert to attack by ferric iron or acid,
and is solubilized by chemicals of which cyanide is the most
commonly used. The gold is finely divided in the mineral
matrix in such a way that even after grinding to a fine
powder, typically <50% of the gold is recovered on
cyanidation. Here, the aim is to use biooxidation to
decompose the mineral matrix and expose the entrapped
gold [20]. This pretreatment process enables greater
access of cyanide to the gold during the subsequent
extraction process, allowing >95% of the gold to be
recovered. Given that the gold is not solubilized during
the biological process, the term bioleaching is inappro-
piate and this treatment strategy is known as biooxidation.

There are many factors that affect the microbial
decomposition of ores. Amongst the most important of
these are the type of mineral to be treated, the tempera-
ture at which the process is carried out and the type of
reactor used.

**Effect of mineral type**

The mineral dissolution reaction is not identical for all
metal sulfides. It has been observed that the oxidation of
different metal sulfides proceeds via different intermedi-
ates [21]. They proposed a thiosulfate mechanism for the
oxidation of acid-insoluble metal sulfides, such as pyrite
(FeS2), molybdenite (MoS2) or tungstenite (WS2), and a
polysulfide mechanism for acid-soluble metal sulfides,
such as sphalerite (ZnS), chalcoprytite (Cu2S) or galena
(PbS).

In the thiosulfate mechanism, solubilization is through
ferric iron attack on the acid-insoluble metal sulfides, with
thiosulfate being the main intermediate and sulfate the
main end-product. Using pyrite as an example, the
reactions proposed by Schippers and Sand [21] are:

\[
\text{FeS}_2 + 6\text{Fe}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{S}_2\text{O}_3^{2-} + 7\text{Fe}^{2+} + 6\text{H}^+ \quad [1]
\]

\[
\text{S}_2\text{O}_3^{2-} + 8\text{Fe}^{3+} + 5\text{H}_2\text{O} \rightarrow 2\text{SO}_4^{2-} + 8\text{Fe}^{2+} + 10\text{H}^+ \quad [2]
\]

In the case of the polysulfide mechanism, solubilization of
the acid-soluble metal sulfide is through a combined attack
by ferric iron and protons, with elemental sulfur as the
main intermediate. This elemental sulfur is relatively
stable, but can be oxidized to sulfate by sulfur-oxidizing
microbes (Eqns [3]–[5]).

\[
\text{MS} + \text{Fe}^{3+} + \text{H}^+ \rightarrow \text{M}^{2+} + 0.5\text{H}_2\text{S}_n + \text{Fe}^{2+} \\
(n \geq 2) \quad [3]
\]

\[
0.5\text{H}_2\text{S}_n + \text{Fe}^{3+} \rightarrow 0.125\text{S}_8 + \text{Fe}^{2+} + \text{H}^+ \quad [4]
\]

\[
0.125\text{S}_8 + 1.5\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{SO}_4^{2-} + 2\text{H}^+ \quad [5]
\]

This explains why strictly sulfur-oxidizing bacteria, such
as At. thiooxidans or At. caldus, are able to leach some
metal sulfides but not others.

The ferrous iron produced during metal dissolution and
bioleaching might also be reoxidized by iron-oxidizing
organisms to ferric iron (Eqn [6]).

\[
2\text{Fe}^{2+} + 0.5\text{O}_2 + 2\text{H}^+ \rightarrow 2\text{Fe}^{3+} + \text{H}_2\text{O} \quad [6]
\]

The role of the microorganisms in the solubilization of
metal sulfides is, therefore, to provide sulfuric acid (Eqn
[5]) for a proton attack and to keep the iron in the oxidized
ferric state (Eqn [6]) for an oxidative attack on the mineral.

**Temperature**

Based on the above, current understanding is that mineral
decomposition is a chemical process, with the role of the
microorganisms being to produce the ferric iron and acid-
containing solutions. Kinetic studies indicate that, as
general rule, the rate of chemical reactions approximately
doubles with every 10 °C rise in temperature. Although the
rate of decomposition is sufficiently fast at 40 or 50 °C for
some minerals, in case of others (e.g. chalcopyrite)
temperatures of > 70 °C are required for the process to
be rapid enough to be economically viable. An increase in
temperature can also improve the yield of copper because
the quantity of sulfur and other oxidation products that
coat the mineral surface (passivation) is reduced. As would
be expected, different types of organisms dominate
mineral degradation processes as the temperature changes.
Microbes that oxidize minerals at 40 or 50 °C are ubiquitous
wherever mineral is exposed to the surface of the earth.
Natural hot-springs in which the water passes through iron-
or sulfur-containing mineral deposits serve as sources of organisms that grow at higher temperatures.

The occurrence of high acidity in hot-spring water
indicates a potential source of mineral decomposing
organisms that grow optimally at the temperature of the spring.

Commercial biomineralization processes
There are two broad categories of biologically-assisted mineral degrading processes. An ore or concentrate is either placed in a heap or dump, where it is irrigated, or a finely milled mineral suspension is placed in a stirred tank where it is vigorously aerated.

Stirred-tank reactor technology
Stirred-tank processes use highly aerated, continuous-flow reactors. Finely ground mineral concentrate or ore is added to the first tank together with inorganic nutrients in the form of ammonia- and phosphate-containing fertilizers. The stirred suspension flows through a series of pH- and temperature-controlled aeration tanks in which the mineral decomposition takes place [22]. Mineral decomposition takes only days in stirred-tank reactors compared with weeks or months in heap reactors. Stirred tank reactors that operate at 40 and 50 °C have proven to be highly robust and very little adaptation is required for the treatment of different mineral types.

One of the major constraints on the operation of stirred-tank reactors is that the quantity of solids (pulp density) that can be maintained in suspension is limited to 20%. At pulp densities > 20%, physical and microbial problems occur. Not only does the liquid become too thick for efficient gas transfer but also the shear force induced by the impellers causes physical damage to the microbial cells. This limitation in solids concentration plus considerably higher capital and running costs than heap reactors has meant that the use of stirred reactors has been restricted to high-value minerals or mineral concentrates.

Current status of stirred-tank reactor processes
Commercial mineral biooxidation processes which use stirred tanks as the reactors are listed in Table 1. With the exception of Youanmi, which used BacTech technology, all of these plants used the Gold Fields proprietary BIOX process. More recently, the Beaconsfield plant in Australia and the Laizhou plant in China (Fig. 1c) have come into production using Mintek-BacTech technology, and the Kasese plant in Uganda uses BRGM (Bureau de Recherches Géologiques et Minières) technology for the recovery of cobaltiferous pyrite. With the exception of the

Table 1. A history of biooxidation tank reactors

<table>
<thead>
<tr>
<th>Plant</th>
<th>Year</th>
<th>Tonnage (d⁻¹)</th>
<th>Total reactor volume (m³)</th>
<th>Design company</th>
<th>Concentrate</th>
<th>Location</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairview BIOX</td>
<td>1986</td>
<td>14</td>
<td>440</td>
<td>GFL/Biomin</td>
<td>Pyrite, 28%; arsenopyrite, 10%</td>
<td>Barberton, SA</td>
<td>Yes</td>
</tr>
<tr>
<td>Expansion 1</td>
<td>1991</td>
<td>35</td>
<td>1075</td>
<td>GFL/Biomin</td>
<td>Pyrite, 28%; arsenopyrite, 18%</td>
<td>Leonora, Western Australia</td>
<td>No¹</td>
</tr>
<tr>
<td>Expansion 2</td>
<td>1999</td>
<td>55</td>
<td>1415</td>
<td>GFL/Biomin</td>
<td>Pyrite, 18%; arsenopyrite, 38%; pyrrhotite, 46%</td>
<td>Brazil</td>
<td>Yes</td>
</tr>
<tr>
<td>Harbour Lights BIOX</td>
<td>1991</td>
<td>40</td>
<td>980</td>
<td>GFL/Biomin</td>
<td>Pyrite, 37%; arsenopyrite, 22%</td>
<td>Western Australia</td>
<td>Yes</td>
</tr>
<tr>
<td>Expansion 1</td>
<td>1994</td>
<td>300</td>
<td>1160</td>
<td>GFL/Biomin</td>
<td>Pyrite, 43%; arsenopyrite, 5%; Pyrite, 6.5%; arsenopyrite, 17%; pyrrhotite, 14%</td>
<td>Western Australia</td>
<td>No</td>
</tr>
<tr>
<td>Expansion 2</td>
<td>1998</td>
<td>300</td>
<td>1487</td>
<td>GFL/Biomin</td>
<td>Pyrite, 35%; arsenopyrite, 57%</td>
<td>Obuasi, Ghana</td>
<td>Yes</td>
</tr>
<tr>
<td>Wiluna BIOX</td>
<td>1993</td>
<td>115</td>
<td>2820</td>
<td>GFL/Biomin</td>
<td>Pyrite, 35%; arsenopyrite, 57%</td>
<td>San Mateo, Peru</td>
<td>Yes</td>
</tr>
<tr>
<td>Expansion 1</td>
<td>1996</td>
<td>154</td>
<td>4230</td>
<td>GFL/Biomin</td>
<td>Pyrite, 80%</td>
<td>Kasese, Uganda</td>
<td>Yes</td>
</tr>
<tr>
<td>Youanmi</td>
<td>1994</td>
<td>120</td>
<td>3000</td>
<td>BacTech</td>
<td>Pyrite, 25–49%; arsenopyrite, 7–15%</td>
<td>Shandong Province, China</td>
<td>Yes</td>
</tr>
<tr>
<td>Ashanti–Sansu BIOX</td>
<td>1994</td>
<td>720</td>
<td>16 200</td>
<td>GFL/Biomin</td>
<td>Pyrite, 25–49%; arsenopyrite, 7–15%</td>
<td>Shandong Province, China</td>
<td>Yes</td>
</tr>
<tr>
<td>Expansion 1</td>
<td>1995</td>
<td>960</td>
<td>21 600</td>
<td>GFL/Biomin</td>
<td>Pyrite, 35%; arsenopyrite, 57%</td>
<td>Shandong Province, China</td>
<td>Yes</td>
</tr>
<tr>
<td>Tamborague BIOX</td>
<td>1998</td>
<td>60</td>
<td>1570</td>
<td>GFL/Biomin</td>
<td>Pyrite, 35%; arsenopyrite, 57%</td>
<td>Kalgoorlie, Australia</td>
<td>No</td>
</tr>
<tr>
<td>KCCL</td>
<td>1998</td>
<td>240</td>
<td>6750</td>
<td>BRGM/Signet/KCCL</td>
<td>Pyrite, 48–59%; arsenopyrite, 7–12%</td>
<td>Shandong Province, China</td>
<td>Yes</td>
</tr>
<tr>
<td>Beaconsfield</td>
<td>1999</td>
<td>68</td>
<td>2310</td>
<td>Mintek–BacTech</td>
<td>Pyrite, 25–49%; arsenopyrite, 7–15%</td>
<td>Shandong Province, China</td>
<td>Yes</td>
</tr>
<tr>
<td>Laizhou</td>
<td>2001</td>
<td>100</td>
<td>4050</td>
<td>Mintek–BacTech</td>
<td>Pyrite, 25–49%; arsenopyrite, 7–15%</td>
<td>Shandong Province, China</td>
<td>Yes</td>
</tr>
</tbody>
</table>

¹Year commissioned.
²Biomin Technologies SA, a wholly owned subsidiary of Gold Fields Ltd (GFL), owns the rights to the BIOX process.
³The mineralogical composition of the concentrate is variable, depending on the run of mine (ROM) ore characteristics.
⁴The Harbour Lights BIOX project was successfully operated until the underground ore and pyrite stock-pile was depleted.
⁵The São Bento mine employs a combination biooxidation–pressure-oxidation circuit.
⁶Bioleaching of cobaltiferous pyrite concentrate (1.37% Co).

http://tibtec.trends.com
Kasese plant, all existing commercial biooxidation tank reactors (Table 1) are gold biobeneficiation plants dominated by Gold Fields (BIOX®) and Mintek–BacTech technology. Stirred-tank leach technology for the recovery of copper, nickel and zinc that should be applicable to a variety of concentrates using moderately thermophilic and mesophilic organisms at pilot and commercial scale has been demonstrated[23] (and see http://www.mintek.co.za and http://www.goldfields.co.za).

All commercially existing plants as well as plants currently in the planning stage (Table 2) have been operated using mesophilic or moderately thermophilic bacteria at average temperatures of 40 and 50 °C, respectively. Exceptions are the BHP Billiton-designed, semicommercial, industrial test reactor (300 m³) in South Africa (Fig. 2), built to test reactor design criteria for the 20 000 tonne copper per annum BioCOP™ prototype plant to be built in Chile for Alliance Copper Ltd, and a Mintek–BacTech three-way joint venture with Peñoles in Mexico, both of which operate at temperatures exceeding 60 °C.

New developments in stirred-tank processes
Satisfactory biooxidation rates of minerals such as pyrite (FeS₂), arsenopyrite (FeAsS), pentlandite (FeNi)₉S₈, sphalerite (ZnS), covellite (CuS) and chalcocite (Cu₂S) are achieved at 40–50 °C. Although increased temperatures yield increased metal dissolution rates, this increase in rate does not usually justify the additional costs associated with high-temperature tank reactors. However, with ores such as chalcopyrite (CuFeS₂) and enargite (Cu₃AsS₄), the situation is different because these are refractory to leaching at 40–50 °C and temperatures preferably as high as 75–80 °C are required[24]. At these high temperatures, difficulties occur that are not as much of a problem at 50 °C or less. For example, the solubility of air is reduced and oxygen gas, rather than air, is used as the oxidant. Evaporation rates are high, and exotic materials for reactor construction (e.g. special grades of stainless steel or ceramics) are required to be able to withstand the very corrosive, high-temperature, acidic environment. Nevertheless, high-temperature mineral oxidation has been successfully demonstrated by BHP Billiton in South Africa. The next step to commercialization is the construction Alliance Copper Ltd’s prototype plant in Chile, a 50:50 joint venture between BHP Billiton and Codelco.

Fig. 1. Commercial tank bioleaching operations: (a) the Sao Bento BIOX® reactor (Brazil); (b) Tamborquque BIOX® plant (Peru); (c) Laizhou Mintek–BacTech Plant (China); and (d) the Sansu BIOX® plant (Ghana).

Fig. 2. Thermophilic archaea-based test reactor (300 m³) with inoculum buildup tanks at Pering (South Africa). To contain corrosion, the tanks are constructed from ceramic composite.
Heap-reactor technology
In a properly designed heap reactor, agglomerated ore is piled onto an impermeable base and supplied with an efficient leach liquor distribution and collection system. Acidic leaching solution is percolated through the crushed ore and microbes growing in the heap produce the ferric iron and acid that result in mineral dissolution and metal solublization. Aeration in such processes can be passive, with air being drawn into the reactor as a result of the flow of liquid, or active, with air blown into the heap through piping installed near the bottom (Fig. 3a). Metal-containing leach solutions that drain from the heap are collected and sent for metal recovery [25].

Heap reactors are cheaper to construct and operate and are therefore more suited to the treatment of lower grade ores than are stirred-tank reactors. However, heap reactors are more difficult to aerate efficiently and to manage. Conditions within stirred reactors are homogeneous, with a constant aeration, pH, temperature, nutrient concentration and microbial growth rate throughout the reactor. In heap reactors, pH gradients occur at both the micro and macro scale. Ores are usually a mixture of mineral and gangue material. Biooxidation of the mineral produces acid, whereas most gangue materials (quartz, mica, chloride, potassium- and calcium-feldspar) are acid-consuming. In practice it is difficult to maintain the solution pH within the range 1.8–2.2. Should the pH rise above 2.5, ferric iron precipitation might occur, which coats the mineral surfaces and reduces the rate of metal solubilization. Similarly, the effective provision of nutrients is more complicated in heap reactors. The most important added nutrient is ammonium but, in areas in which the pH is too high, the addition of a monovalent cation such as ammonium can result in the formation of jarosite precipitate, which removes ferric iron from solution and also coats mineral surfaces. Heaps are usually irrigated with raffinate (recycled leach solution from which the metal has been removed) and a gradual build up of inhibitory ions, such as sulfates and aluminum, has to be avoided.

Heap reactors are also more difficult to inoculate than are tank reactors. Different microbes exhibit different mineral adsorption isotherms, and this might cause uneven initial microbial species distribution within a heap. Eventually the microbial population will become more evenly distributed as a result of microbial mobility, which occurs during heap irrigation. However, deliberate inoculation during heap construction reduces this variation and can speed up the process. When a heap is constructed, fine material is agglomerated to the coarse particles using acid and a microbial inoculum can be added at this stage. A disadvantage of this option is that if the levels of acid used during agglomeration are too high, cell viability can be reduced. Consistency of microbial distribution is not a problem in stirred-tank processes.

Even in carefully designed heap reactors, larger particle sizes, less effective aeration and reduced process control make the process less efficient than stirred-tank reactors. This results in the biomineralization process taking months rather than days.

Table 2. Future biooxidation tank reactors

<table>
<thead>
<tr>
<th>Project</th>
<th>Tonnage (d⁻¹)</th>
<th>Total reactor volumes (m³)</th>
<th>Technology supplier</th>
<th>Concentrate</th>
<th>Location</th>
<th>Primary metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amantaytau BIOX®</td>
<td>1458</td>
<td>23 400</td>
<td>GFL/Biomin Technologies SA</td>
<td>Pyrite, 46%; arsenopyrite 3%</td>
<td>Uzbekistan</td>
<td>Au</td>
</tr>
<tr>
<td>Perseverance BIOX®</td>
<td>126</td>
<td>3185</td>
<td>GFL/Biomin Technologies SA</td>
<td>Pyrite, 28%; arsenopyrite 18%</td>
<td>Victoria, Australia</td>
<td>Au</td>
</tr>
<tr>
<td>TVX BIOX®</td>
<td>713</td>
<td>14 160</td>
<td>GFL/Biomin Technologies SA</td>
<td>Pyrite, 52%; arsenopyrite 28%</td>
<td>Greece</td>
<td>Au</td>
</tr>
<tr>
<td>Kokpatas BIOX®</td>
<td>2163</td>
<td>43 800</td>
<td>GFL/Biomin Technologies SA</td>
<td>Pyrite, 45%; arsenopyrite 11%</td>
<td>Uzbekistan</td>
<td>Au</td>
</tr>
<tr>
<td>Alliance Copper Ltd BioCOP™</td>
<td>238</td>
<td>8226</td>
<td>BHP Billiton</td>
<td>Pyrite, 33%; enargite 23.7%;</td>
<td>Chuquicamata, Chile</td>
<td>Cu</td>
</tr>
</tbody>
</table>

*aThe last feasibility study for the treatment of the TVX concentrate employed a combination biooxidation–pressure–oxidation circuit.

Fig. 3. Heap-leaching operation at Cerro Colorado in Chile. (a) Heaps with aeration blowers, (b) insulating thermofilm and (c) buried irrigation drippers.
Current status of heap-leaching technology

A substantial number of heap-leaching metal recovery processes are in operation, some for many years. Heap leaching has been applied mainly to the treatment of copper ores (Table 3); however, it has been shown that heap technology can be applied in the pretreatment of gold-bearing ores before taking up the heap and gold-recovery by cyanidation [26]. Many heap-leach processes have targeted the extraction of marginal ores that are not suitable for the production of concentrates or smelting. Development of heap-leaching technology has been largely engineering-focused rather than microbiology-focused. The main advances have therefore come from improved acidification methods, solution management and heat containment. Much of the progress in heap leaching can be attributed to research into the modeling of leach liquor distribution, oxygen diffusion and heat management [27,28]. In addition, a substantial amount of unpublished operational research has been carried out by companies such as Newmont Mining, Phelps Dodge, BHP Billiton, POT-Titan and Rio Tinto.

New developments in heap-leach processing

Much like stirred-tank technology, increasing the temperature of a heap improves chemical solubilization rates and offers the potential for otherwise slow-reacting ores to be processed. Increased temperatures in heaps have been achieved by improved aeration regimens, based on modeling predictions and by using insulation. Aeration results in increased microbial activity and a corresponding increase in energy release, mainly from exothermic sulphide oxidation reactions. Optimization of aeration is important to ensure suitable levels of microbial activity and energy release whilst avoiding heat stripping from the heap that would occur as a result of over-aeration. Thermofilms (e.g., polyethylene sheets made for agricultural use) have been used at several heap leaching operations (Fig. 3b) to reduce heat radiation and maintain heap temperature. Improvements in solution management have also resulted in improved heat retention, including the use of drippers as irrigation devices, rather than sprayers, to minimize heat and evaporation losses. Dripper tubes can be buried (~15 cm) to provide a measure of insulation from low temperature surface conditions (Fig. 3c).

Heap-leaching processes are typically used for the treatment of low-grade ores, but heap-leaching systems can also be used for the treatment of concentrates. GeoBiotics LLC has developed a hybrid technology (GEOCOAT™) aimed at obtaining most of the low-construction and operation costs of heap reactors as well as the high reaction rates associated stirred-tank reactors. Heap reactors are constructed using inert rock or low-grade ore as a support material onto which a thin layer of milled mineral concentrate is agglomerated [29]. The microbial inoculum is introduced via a sprayer system during stacking of the heap. The thin mineral coating facilitates rapid mineral leaching rates. Although leaching periods are usually greater than for tank leaching, they are considerably shorter than for typical heap-leaching systems. This technology was initially developed for the treatment of refractory gold, but it is also suitable for treatment of nickel, copper and cobalt concentrates [30]. GeoBiotics LLC have recently successfully applied this technology to sphalerite (ZnS) concentrates at the Rosh Pinah mine of Kumba Resources in Namibia.

Future of bioleaching

The technical feasibility and robustness of heap- and tank-bioleaching processes for the recovery of a variety metals from ores that operate at temperatures from ambient to 50 °C has clearly been demonstrated. Once commercial-scale, high-temperature processes have been designed, the variety of minerals that will become amenable to biominalization will increase. Although the commercial robustness of microbes that thrive at temperatures >55 °C is not yet well-proven, it appears that one can isolate iron- or and sulfur-oxidizing organisms for what- ever temperature is required, up to at least 80 °C. Therefore, where suitable microbes for mineral biodegra- dation at a given temperature are not yet known, they can probably be found. Results already obtained from pilot-scale stirred-tank processes that operate at temperatures as high as 78 °C are promising. Although some minerals contain substances that inhibit microbial activity (e.g.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cu tonnage (y−1)*</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyprus Miami Mining Corp</td>
<td>73 000</td>
<td>Miami, AZ, USA</td>
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<tr>
<td>Cyprus Serrita Corporation</td>
<td>21 800</td>
<td>Green Valley, AZ, USA</td>
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<td>Tyrone, NM, USA</td>
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<td>Burro Chief Copper Co–Phelps Dodge Chino Mines Co.</td>
<td>66 200</td>
<td>Santa Rita, NM, USA</td>
</tr>
<tr>
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<td>21 000</td>
<td>Marana, AZ, USA</td>
</tr>
<tr>
<td>BHP Billiton Billiton Copper San Manuel</td>
<td>22 680</td>
<td>San Manuel, AZ, USA</td>
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<tr>
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<td>Miami, AZ, USA</td>
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<tr>
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</tr>
<tr>
<td>Sociedad Minera Cerro Verde S.A.</td>
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</tr>
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<td>Sociedad Contractual Minera El Abra</td>
<td>225 000</td>
<td>Region II (Calama), Chile</td>
</tr>
<tr>
<td>BHP Billiton Compania Minera Cerro Colorado</td>
<td>100 000</td>
<td>Mamina, Chile</td>
</tr>
<tr>
<td>Codelco Chile–Division Radimiro Tomic</td>
<td>180 000</td>
<td>Region II (Calama), Chile</td>
</tr>
<tr>
<td>Codelco Chile–Division El Teniente</td>
<td>4800</td>
<td>Sewell Rancagua, Chile</td>
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<tr>
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<td>5000</td>
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</tr>
<tr>
<td>Compania Minera Zaldívar</td>
<td>131 500</td>
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</tr>
<tr>
<td>Girilambone Copper Co.</td>
<td>17 500</td>
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</tr>
<tr>
<td>Mt Cuthbert Copper Co.</td>
<td>4900</td>
<td>Queensland, Australia</td>
</tr>
</tbody>
</table>

*1998 production.
silver or chloride), in general, limitations to the application of bioleaching to metal recovery from many iron- and sulfide-containing minerals have less to do with microbial deficiencies than with technical, engineering and economic considerations.

The most important challenge in the development of new heap-leach processes is the inability to generate sufficient heat when the mineral sulfide content is low. Most other challenges concern the management and control of heap-leaching process variables. With tank-leaching processes, it is mainly the cost of construction and operation and sometimes metal purification following bioleaching that limits their use. Most of the technical challenges can be solved at a cost, provided that the value of the metal recovered allows for this. Although bioleaching provides the possibility of recovering metals from low-grade deposits that would otherwise be considered waste, its application greatly depends on the value of the metal to be recovered. A major challenge is to find a suitable match between an ore body and bioleaching technology. For example, the technology for nickel recovery using the BioNIC process [23] has been thoroughly tested, but as yet no ore body of a suitable concentration and size has been identified to allow economic recovery at current nickel prices.

Increased concern regarding the effect of mining on the environment is likely to improve the competitive advantage of microbially-based metal recovery processes. The enforcement of more stringent legislation to limit environmental pollution (e.g. uncontrolled metal and acid leaching from dumps, or arsenic emission from smelters) would make bioleaching more attractive.

The use of bioleaching in metal recovery is now well-established. Furthermore, its application is likely to grow because, where a suitable mineral deposit is available, it offers advantages of operational simplicity, minimum environmental impact and low capital, plus operating costs that no other technology can match [31].

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References