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# BIOMINING

# EXTRACTING METALS WITH MICROORGANISMS

Biomining is a generic term that describes the processing of metal-containing ores and concentrates of metal-containing ores using microbiological technology. Biomining has application as an alternative to more traditional physical-chemical methods of mineral processing. Commercial practices of biomining are usually partitioned into two separate processes: *minerals biooxidation* and *bioleaching*. Both are processes that use naturally-occurring microorganisms to extract metals from sulfide-bearing minerals. *Minerals biooxidation* refers to the process when it is applied to enhance the extraction of gold and silver, whereas *bioleaching* usually refers to the extraction of base metals, such as zinc, copper, and nickel. However, the two terms are often used interchangeably. Collectively, minerals bio-oxidation and bioleaching are commercially-proven, biohydrometallurgical or biomining processes that are economic alternatives to smelting, roasting, and pressure oxidation to treat base- and precious-metals associated with sulfide minerals.

Biomining is commercially employed in four different engineered processes:

- **Dump bioleaching** extracts copper from sulfide ores that are too low-grade to process by any other method – this process has been used since the mid-1950s
- **Heap bioleaching,** which has been used since the 1980s, extracts copper from crushed sulfide minerals placed on engineered pads
- **Heap minerals biooxidation** pre-treats gold ores in which the gold particles are locked in sulfide minerals, significantly enhancing gold recovery
- **Stirred-tank minerals biooxidation** enhances gold recovery from mineral concentrates in which the gold is locked in sulfide minerals and **stirred-tank bioleaching** extracts base metals from concentrates of metal-containing sulfide ores.

This fact sheet answers frequently asked questions about bioleaching and minerals biooxidation and relates the processes to the recovery of gold, silver, copper, zinc, nickel, cobalt and other base metals from ores and concentrates of metal-containing ores:

- What is the history of the technology?
- What is the nature of the micro-organisms that are used?
- How are the biotechnical processes to extract metals carried out?
- What are the waste products and how are they managed?
- Who uses the technology?
- What are the advantages and disadvantages of the processes?

## WHAT IS THE HISTORY OF BIOLEACHING/MINERALS BIOOXIDATION?

The application of biomining processes predates by centuries the understanding of the role of microorganisms in metals extraction. Bioleaching appears to have been carried out in China at least 100-200 years BCE and in Europe and Scandinavia at least as far back as the second century CE. However, the modern era of bioleaching began with the discovery of the bacterium, T*hiobacillus 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 ferro-oxidans* 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. This biomining process entails stacking the run-of-mine material in piles to depths of up to 60 meters (200 feet), applying water-diluted sulfuric acid over the ore piles, allowing the microorganisms to grow in the ore pile, and recovering the dissolved copper from the acidic solution that emerges from the bottom of the pile. This process, called **dump leaching**, is widely practiced today by mining companies throughout the world as an adjunct to smelting and hydrometallurgical technologies to extract copper from ores that are too low-grade (usually less than 0.5% copper) to process by other methods.

In the 1980s two new biomining processes, **heap bioleaching** and **stirred-tank minerals biooxidation**, were developed and commercially applied. The 1990s saw the development and commercial application of **heap minerals biooxidation**.

## WHAT MICROORGANISMS ARE USED IN BIOMINING PROCESSES?

The natural habitats of all microorganisms used in bioleaching and minerals biooxidation are acid, hot springs (for example, Yellowstone National Park), volcanic areas, natural outcroppings of sulfide minerals, and mining areas where sulfide minerals have been exposed to air.

All of the microorganisms used in biomining have several things in common. They

- Are single-celled organisms that multiply by simple cell division
- Derive energy for growth and cell functioning by oxidizing iron and sulfur. Oxidation involves the removal of electrons from a substance. In biomining processes the microbes remove electrons from dissolved iron (ferrous iron) converting it to another form of iron (ferric iron); electrons are removed from sulfur converting it to sulfuric acid. In contrast, humans, animals and many other microorganisms oxidize carbon-containing material as a food source
- Obtain carbon for their cellular bodies from carbon dioxide ($CO_2$) in the atmosphere
- Require oxygen taken from the atmosphere
- Require a sulfuric acid environment to grow. The acidity must be less than pH 2.5, which is more acidic than vinegar.

The biomining microorganisms do not cause diseases in humans, animals or plants. Because their food source is inorganic (sulfur and iron) and because they must live in a sulfuric acid environment, they can not survive in or on plants and animals.

The same microbes used in biomining can cause acid rock drainage when sulfide minerals are left exposed to air for long periods of time. Legacy wastes from coal and hard-rock mining activities in the 19th and early 20th centuries have been naturally colonized by the microbes resulting in acid pollution of some rivers and streams.

Since the discovery in the 1940s of *Thiobacillus ferrooxidans* (now known as *Acidithiobacillus ferrooxidans*), many more microorganisms have been discovered that are also involved in metals extraction. The microbes can be conveniently grouped within temperature ranges at which they grow and where they are found in the natural environment:

**Ambient temperature bacteria (mesophiles).** These cylindrical-shaped biomining bacteria are about 1 micrometer (µm) long by ½ µm in diameter (1 micrometer is 4/100,000 of an inch). About 1,500 of these bacteria could lay end-to-end across a pin head. They only grow and function from about 10°C to 40°C (50°F to 104°F). If the temperature is too low, these bacteria become dormant. If the temperature exceeds 45°C (113°C), the organisms die when their proteins coagulate similar to cooking an egg. *Acidithiobacillus ferrooxidans* belong to this group of bacteria. Others include *Leptospirillum ferrooxidans* (see Figure 1) and species of *Ferroplasma*.

**Moderately-thermophilic (heat-loving) bacteria.** These bacteria are similar to the "mesophilic" biomining bacteria, except they are somewhat larger in length – about 2 to 5 micrometers long (see Figure 2) – and they only grow and perform when the temperature exceeds 40°C (104°F). The moderate thermophiles die when the temperature exceeds about 60°C (140°F). Examples of moderate thermophiles are species of *Sulfobacillus* and *Acidithiobacillus caldus*.

**Extremely thermophilic *Archaea.*** While similar in size (one micrometer in diameter) to bacteria, *Archaea* have a different molecular organization. In the tree of life, *Archaea* occupy the lowest branch and are extant members of an offshoot of primitive microbes. They have a spherical shape (see Figure 3) and characteristically lack a rigid cell wall; rather the contents of the single cell are enclosed by a membrane. These microbes, nevertheless, are extremely robust growing and performing only at temperatures between 60°C (140°F) and 85°C (185°F). Examples of extremely-thermophilic *Archaea* used in biomining are *Acidianus brierleyi*, *Sulfolobus metallicus* and *Metallosphaera sedula*.

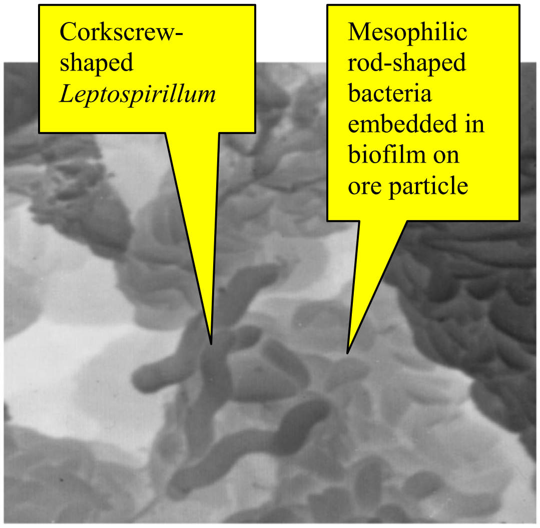

**Fig. 1** Scanning electron microscope photograph illustrating the typical spiral shape of a strain of *Leptospirillum*. Rod-shaped bacteria in different stages of entrapment in a biofilm on ore particles are also visible. SOURCE: Rawlings, D.E. 2004. Microbially assisted dissolution of minerals and its use in the mining industry. *Pure and Applied Chemistry*, vol. 64, no. 4, pp. 847-859.

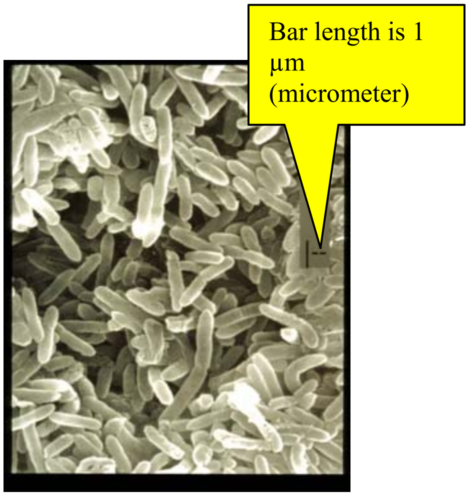

**Fig. 2** Scanning electron micrograph of moderately thermophilic bacteria, illustrating short chains of the organisms. Bacterial cells are about 2-5 µm long and 0.5 to 1 µm in diameter. Photomicrograph is courtesy of Brierley Consultancy LLC.

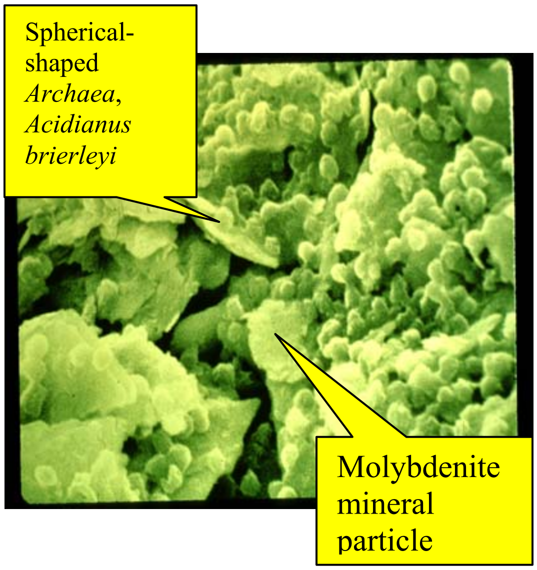

**Fig. 3** Scanning electron micrograph of *Acidianus brierleyi*, an extremely thermophilic *Archaea*, growing on molybdenite, a molybdenum sulfide mineral. Photomicrograph courtesy of Brierley Consultancy LLC.

## WHAT IS THE ROLE OF MICROBES IN BIOMINING?

We have a good understanding of the exact role of microbes in biomining, thanks to today's sophisticated instrumentation that can examine materials at the atomic level. Although many microbes float freely in the solution around the minerals, many microbes attach to the mineral particles forming a biofilm (Figure 1) – a single layer of cells embedded in a matrix composed of sugars secreted by the microbes. The microbes, whether they are freely floating or whether they are in the biofilm, continuously devour their food sources – iron (chemically represented as $Fe^{2+}$) and sulfur. The product of the microbial conversion of iron is "ferric iron", chemically represented as "$Fe^{3+}$". Ferric iron is a powerful oxidizing agent, corroding metal sulfide minerals (for example, pyrite, arsenopyrite, chalcocite, and sphalerite) and degrading them into a dissolved metal, such as copper, zinc, and more iron -- the latter the food source for the microbes. The sulfide portion of the mineral is converted by the microbes to sulfuric acid.

In some precious-metal mineral deposits gold occurs as micrometer-sized particles that are occluded, or locked, within sulfide minerals, principally pyrite (an iron sulfide mineral) (see Figure 4) and arsenopyrite (an arsenic containing iron sulfide mineral). To effectively recover the precious metals, the sulfides must be degraded (oxidized) (see Figure 5) to expose the precious metals. Once the sulfides are sufficiently degraded to expose the gold and silver, a dilute solution of cyanide is used to dissolve the precious metals. If the occluded gold and silver are not exposed by breaking down the sulfide minerals, the cyanide can not "see" the precious metals and consequently recoveries are very low. The ferric iron that is produced by the microorganisms is the chemical agent that breaks-down (oxidizes) the sulfide minerals. The microorganisms can be thought of as the manufacturing facility for producing the ferric iron.

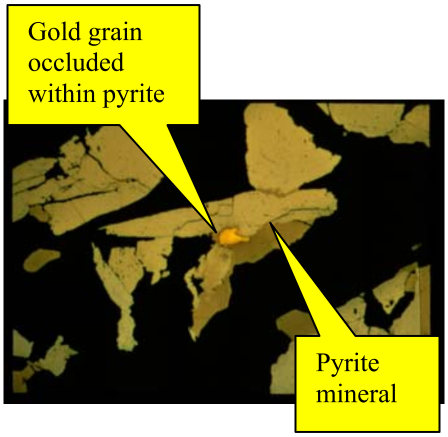

**Fig. 4** Micrograph showing a gold grain occluded within the sulfide mineral, pyrite. To efficiently dissolve this gold grain with dilute cyanide or other gold-dissolving reagent, the pyrite must first be oxidized using ferric iron produced by microorganisms. Photomicrograph courtesy of Newmont Mining Corporation.

During the minerals biooxidation of the pyrite and arsenopyrite that occlude the gold, the ferric iron produced by the microorganisms also attacks any base-metal sulfide minerals that are present in the ore. This causes metals such as copper, zinc, nickel and cobalt to dissolve in the weak sulfuric acid. These metals can be recovered from the solution.

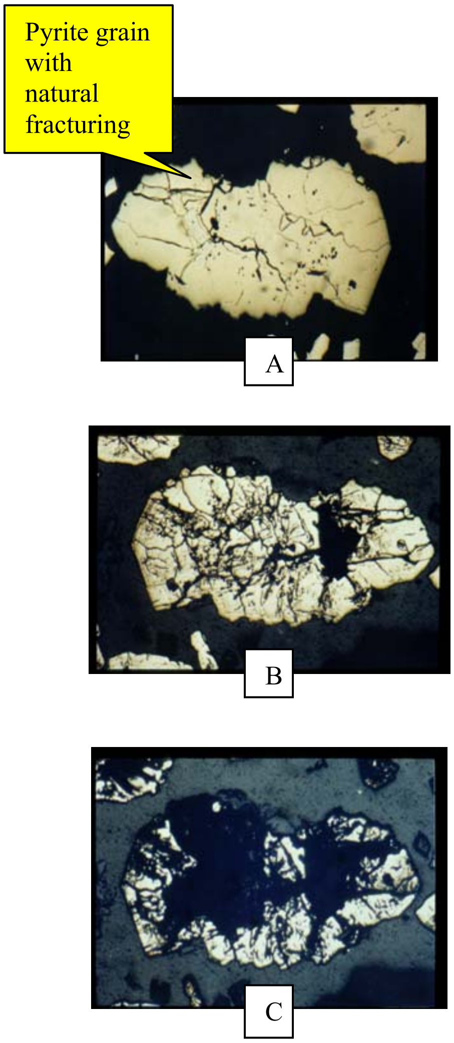

**Fig 5** Series of micrographs showing the oxidation (degradation) of pyrite in the presence of microorganisms producing ferric iron: (A) original pyrite grain with natural fracturing; (B) pyrite grain mid-way through oxidation in the presence of microbes (note that oxidation first occurs along the natural fractures – black portions - within the mineral grain); (C) pyrite grain is nearly completely oxidized (black portion) by the microbially-produced ferric iron. Photomicrograph courtesy of Newmont Mining Corporation.

## HOW ARE BIOMINING PROCESSES ENGINEERED?

Biomining is applied using four different engineered methods: **dump bioleaching, heap bioleaching, heap minerals biooxidation**, and **stirred tank bioleaching /minerals biooxidation**

**Dump Bioleaching**. First commercially applied in the 1950s, dump leaching remains an important process for the copper mining industry. At many open pit operations a very large amount of material is 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 tons of run-of-mine ore and are often several hundred feet deep (see Figure 6). Water containing a small amount of sulfuric acid is applied to the top surface of the dump using sprinklers or drippers. As the acidic solution percolates through the dump, favorable conditions develop for the growth of naturally-occurring microorganisms, which catalyze the oxidation of the copper sulfide minerals.

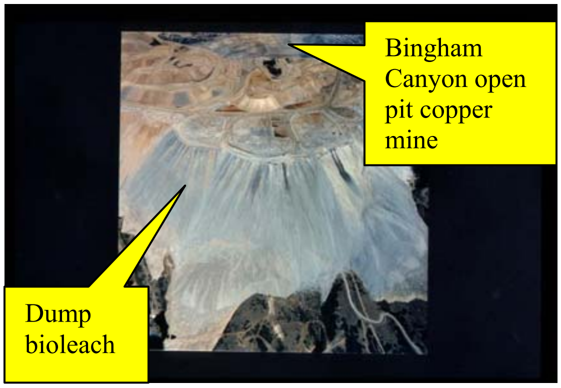

**Fig. 6** Copper dump bioleach operation at Bingham Canyon Mine near Salt Lake City, Utah. Photo courtesy of Brierley Consultancy LLC.

Leaching of copper from dumps is measured in decades, because of the large particle size of the marginal-grade ore placed in dumps, inefficiencies in solution transport through the dump, and generally poor aeration of the dump 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. The leach solution (called "raffinate") 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 metric tonnes (198,450 – 220,500 tons) of cathode copper per year over the next 40 years, making Escondida the largest dump bioleach operation in the world.

**Heap Bioleaching.** Heap bioleaching is widely practiced around the world for the extraction of copper from "secondary copper ores" (chalcocite and covellite)[1]. The ore is crushed to about ¾ inch or less and agglomerated in rotating drums with water containing sulfuric acid 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 six to 10 meters (20 to 33 feet) most often with automated stackers (see Figure 7). 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 one million per gram of ore), facilitating copper extraction. The maximum copper leached from heap bioleach operations is 80-85% requiring 250- to 350-days of on-pad leaching to achieve this recovery.

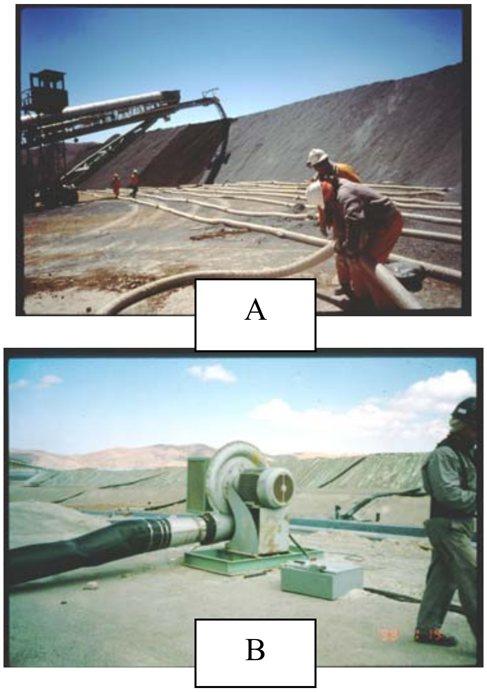

**Fig. 7** (A) Stacking acid-conditioned secondary copper ore on engineered leach pad at TeckCominco's Quebrada Blanca Mine in Chile. (B) Blowers external to the heap provide air that is distributed to the microorganisms through perforated plastic pipes laid beneath the heap. Photos courtesy of Compañía Quebrada Blanca S.A.

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[1] In recent years heap bioleaching of zinc and nickel from sulfide minerals has also been developed. TeckCominco Limited pilot tested heap bioleaching of sphalerite, a zinc sulfide mineral. Nickel sulfide heap bioleaching is currently being demonstrated at the Talvivaara Mine in Finland.

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 one million metric tonnes per annum - of the total global annual production of approximately 17 million metric tonnes of copper. Table 1 lists both historical and current industrial, copper heap bioleach operations. This does not include copper recovered using dump bioleaching processes. It is estimated that if dump bioleaching is included some 15-20% of the world's copper production is attributable to bioleaching.

When bioleaching is complete in the heap, some operations remove the leached ore and stack it on another lined pad in a permanent location where bioleaching continues. Other operations place an impermeable liner on top of the bioleached heap, install air and drain lines on the pad and stack more ore on top of the previous heap. Still other operations place additional stacks, call "lifts", immediately on top of the bioleached ore and allow the leach solutions to percolate through multiple lifts.

At closure of the operation, all heaps are rinsed with fresh water to remove residual dissolved copper and the heaps are thoroughly drained. All solutions are collected and evaporated with any residues placed on the heaps. The heaps are recontoured, capped with clay or synthetic barrier material to minimize the entry of air and water, covered with soil and seeded. Without the oxygen in air, the microbes die. This closure practice mitigates acid rock drainage. Any drainage that does come from the closed heap leach operation is collected and neutralized with lime before discharge.

**Heap Biooxidation Pretreatment.** In 1999 Newmont Mining Corporation began commercially applying heap leach technology to pre-treat "sulfidic-refractory" gold ores. These are ores in which microscopic gold particles are locked, or occluded, within a sulfide mineral, usually pyrite, arsenopyrite, or both (see Figure 4). To obtain good gold recovery the sulfide minerals must be degraded (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 the three groups of microorganisms described earlier – the ambient temperature bacteria, the moderately-thermophilic bacteria, and the 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 using an agglomerating drum. The crushed and inoculated ore is stacked on HDPE-lined pads with aeration and drain lines (see Figure 8).

As the pyrite and arsenopyrite minerals begin to oxidize, heat is generated and the heaps heat to above 60°C (140°F). 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 metal of value – gold – is left in the heap. The leach solution discharging from the heap contains dissolved iron, arsenic and other metals from sulfide minerals in the ore. This solution is used as the inoculum and also as the irrigation solution for the next heap.

The heap is removed from the leach pad when the biooxidation is complete and lime is added to condition the biooxidized ore for cyanide leaching that extracts the gold.

**TABLE 1** Industrial copper heap bioleaching operations throughout the world[1].

| **Industrial plant & location/ owner** | **Cathode copper production (metric tonnes/year)** | **Operational status** |
|---|---|---|
| Lo Aguirre, Chile/<br>Sociedad Minera Pudahuel Ltda | 15,000 | 1980 – 1996<br>(mine closure due to ore deposit depletion) |
| Mount Gordon (formerly Gunpowder), Australia/ Western Metals Ltd. | 33,000 | 1991 - Present |
| Mt. Leyshon, Australia/<br>(formerly Normandy Poseidon) | 750 | 1992 – 1995<br>(stockpile depleted) |
| Cerro Colorado, Chile/<br>BHPBilliton | 115,000 | 1993 – Present |
| Girilambone, Australia/<br>Straits Resources Ltd & Nord Pacific Limited | 14,000 | 1993 – 2003<br>(ore depleted) |
| Ivan-Zar, Chile/<br>Compañía Minera Milpro | 10,000 – 12,000 | 1994 - Present |
| Punta del Cobre, Chile/<br>Sociedad Punta del Cobre, S.A. | 7,000 – 8,000 | 1994 - Present |
| Quebrada Blanca, Chile/<br>TeckCominco Ltd. | 75,000 | 1994 – Present |
| Andacollo Cobre, Chile/<br>Aur Resources, del Pacifico & ENAMI | 21,000 | 1996 - Present |
| Dos Amigos, Chile/CEMIN | 10,000) | 1996 - Present |
| Zaldivar, Chile/Barrick Gold Corp. | 150,000 | 1998 - Present |
| Lomas Bayas, Chile/XSTRATA plc | 60,000 | 1998 - Present |
| Cerro Verde, Peru/<br>FreeportMcMoran & Buenaventura | 54,200 | 1997 - Present |
| Lince II, Chile/ | 27,000 | |
| Monywa, Myanmar/Ivanhoe Mines Ltd, Myanmar No.1 Mining Enterprise | 40,000 | 1998 - Present |
| Nifty Copper, Australia/Straits Resources Ltd. | 16,000 | 1998 - Present |
| Morenci, Arizona/<br>FreeportMcMoran | 380,000 | 2001 - Present |
| Lisbon Valley, Utah/<br>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/ | 17,000 | 2006 - Present |

[1] Copper dump bioleach operations are not included in this table. About 7% of the world's 17 million metric tonnes of copper is produced by heap bioleaching. Another 8-13% of the world's copper is produced by dump bioleaching.

Microorganisms in the ore are destroyed by the lime. Cyanide leaching can be accomplished in another heap or the oxidized and lime-conditioned ore can be ground and cyanide leached in a mill.

Newmont Mining Corporation has been commercially applying heap biooxidation pretreatment to low-grade, sulfidic- refractory gold ore at its Gold Quarry operation near Carlin, Nevada since 1999 (Figure 8).

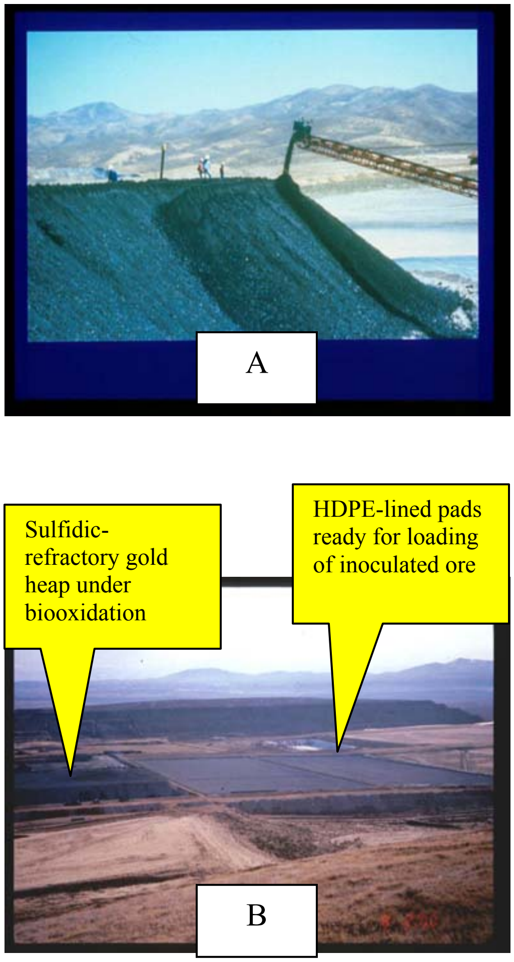

**Fig. 8** (A) Stacking microbially-inoculated, sulfidic-refractory gold ore at Newmont's Gold Quarry Mine in Nevada. (B) Plastic-lined pads on the right are ready for loading the ore for biooxidation with a heap under biooxidation on the left. Photos courtesy of Newmont Mining Corporation.

Between 2000 and May 2005 over 13 tons (12,172 kilograms) of gold were recovered through heap biooxidation of low-grade ore averaging about 0.07 ounces per ton[2].

**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 (bioreactors), each as large as 1,380 cubic meters (364,320 gallons) (see Figure 9), 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 a billion 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 three to five days.

**Fig. 9** Aerated stirred tank bioleach plant. Courtesy of Kasese Cobalt Company, Uganda.

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[2] No publicly-available data were reported for the period following mid-2005.

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. In addition to those listed in Table 2, the Kasese Cobalt Company operates a stirred-tank bioleach plant to recover cobalt (Figure 9).

## SUMMARY

Bioleaching has been commercially practiced for half a century to economically extract copper from marginal-grade ores. In the last 25 years new developments in microbiology coupled with engineering enhancements have yielded heap bioleaching for copper ores, heap biooxidation for pretreatment of sulfidic-refractory gold ores and aerated, continuous stirred-tank reactor processes for base- and precious metal mineral concentrates. All of these biomining technologies are widely practiced on a commercial basis throughout the world today with bioleaching accounting for some 15-20% of the world's total copper production of approximately 17 million metric tonnes of copper.

### FREQUENTLY ASKED QUESTIONS

***Are the microbes used in biomining processes genetically altered?*** *No. All of the microorganisms used in biomining occur in nature and are inhabitants of acid hot springs, volcanic regions, sulfide mineral outcroppings and at mining operations where sulfide minerals are exposed to air. We do not genetically manipulate these naturally-occurring organisms before they are employed in commercial mining operations.*

**What is the life-span of the biomining microorganisms?** *Unlike humans, animals and plants, microorganisms reproduce by doubling. That is, when the microbe has abundant food (iron and sulfur for the biomining microbes) and optimal conditions (sufficient oxygen, carbon dioxide and a sulfuric acid environment) a microbe will simply divide. One microbe becomes two, two becomes four, four becomes 16 and so forth. This logarithmic division occurs until something, such as lack of food or oxygen or an unfavorable pH, prevents the organisms from further division. In heap minerals bio-oxidation for pre-treating gold ores, there are about one million microbes per gram of ore. In continuous stirred-tank bioleaching/minerals biooxidation the number of microbes exceeds one billion per milliliter of solution.*

**Can biomining be effectively used in extreme environments such as high altitudes and in cold environments?** Yes. *High altitudes have no affect on the biomining microorganisms. Additional air must be supplied to the organisms to give them sufficient oxygen for optimal performance, because as elevation increases, the partial pressure of oxygen in the air decreases. For example, at about 15,000 feet above sea level, air has about half of the oxygen as air at sea level.*

*Cold temperature slows both the rate of microbial activity and the break-down of the sulfide minerals. However, the break-down of sulfide minerals, particularly pyrite oxidation, produces a lot of heat. Therefore, it is sometimes necessary in biomining to use the high-temperature (thermophilic) microorganisms, because the amount of heat that is produced kills the mesophilic (ambient temperature) microorganisms*

**Do biomining microorganisms produce dangerous waste products?** *No. The solutions that are generated from biomining are processed to recover base metals (e.g., zinc and copper) and then recycled for reuse; if solutions must be discharged from the mine site, they are treated with limestone and/or lime to neutralize them, which causes dissolved metals to drop out of (precipitate from) the solution. The metals are either reclaimed or discarded in an environmentally approved disposal facility. Precious metal ores that are biooxidized are treated with lime and leached with cyanide to extract gold and silver; lime and destroy the microorganisms. The solid residues left from cyanide leaching or bioleaching of base metal ores are either disposed in an environmentally-approved tailings dam for finely-ground material or the heaps are subjected to approved closure procedures.*

**TABLE 2** Industrial plants using continuous stirred-tank bioleach operations for pretreating sulfidic-refractory gold concentrates

| Industrial plant location and owner | Design capacity-daily tonnes concentrate (metric tonnes) | Operating Years | Performance/Reason for Closure |
|---|---|---|---|
| Fairview, Barberton, South Africa<br>Barberton Mines Ltd. | 55 | 1986 – Present | Exceeding expectations-treating 72 tpd |
| Sao Bento, Brazil<br>Eldorado Gold Corp. | 380 | 1991 – Present | Currently operating at reduced capacity (1 of 3 BIOX® reactors in operation) |
| Harbour Lights, Western Australia | 40 | 1991 - 1994 | Ore deposit depleted |
| Wiluna, Western Australia<br>Agincourt Resources Ltd. | 158 | 1993 - Present | |
| Ashanti, Obuasi, Ghana<br>AngloGold Ashanti Limited | 960 | 1994 – Present | Reduction in treatment rate to 600 tpd due to facilities closure & flotation circuit upgrade |
| Youanmi, Western Australia<br>Goldcrest Resources | 120 | 1994 – 1998 | High underground mining cost resulted in closure of all operations |
| Tamboraque, San Mateo, Peru<br>Iamgold Corp. and Minera Lizandro Proano SA | 60 | 1998 – 2003 Restarted in 2006 | |
| Beaconsfield, Tasmania, Australia<br>Beaconsfield Gold NL | ~70 | 2000 - Present | |
| Laizhou, Shandong Province, China<br>Golden China Resources (Sino Gold Mining Limited) | ~100 | 2001 – Present | |
| Suzdal, Kazakhstan<br>Celtic Resources Holdings Ltd. | 196 | 2005 - Present | |
| Fosterville, Victoria, Australia<br>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 | 1,069 | 2008 - | Commissioned in 2007 |

**Can the biomining microbes escape from the heap or bioreactor and damage anything?** *These microorganisms exist in the environment only where conditions are suitable (that is, where there are sources of iron and sulfur that can be oxidized, air, and a sulfuric acid environment). They already exist naturally in acid hot springs, volcanic areas and where sulfide minerals are exposed to air. Whether the microbes are from a hot spring, a volcanic area or from a biomining operation, if the organisms find themselves in an environment where there is no suitable food or if the pH is too high, they die.*

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March 2008

## ABOUT THE AUTHOR

Dr. Corale L. Brierley provides consultation to the mining and chemical industries and government agencies. She offer clients expertise and experience in (1) minerals biooxidation/ bioleaching, (2) management of metal-bearing aqueous, solid and radioactive wastes, and (3) market analyses and business development. Dr. Brierley is well published with over 80 technical publications and five patents and is internationally recognized resulting from a 30+-year career, comprising 15 years as an international consultant; two years with Newmont Mining Corporation as Head of Environmental Process Development; eight years of managing Advanced Minerals Technology Inc., a metal's biotechnology company; and 10 years of applied research, development and teaching in her fields of expertise at New Mexico Institute of Mining and Technology. Dr. Brierley is a member of the Society of Mining Engineers and the Mining & Metallurgical Society of America and has served on numerous boards, panels and committees for the National Academies and other organizations. She was inducted in 1999 into the U.S. National Academy of Engineering for "innovations applying biotechnology to mine production and remediation". Academy membership is among the highest professional distinctions accorded an engineer and honors those who have demonstrated unusual accomplishment in the pioneering of new and developing fields of technology. Dr. Brierley is the 2008 recipient of AIME’s (American Institute of Mining, Metallurgical & Petroleum Engineers) James Douglas Gold Medal Award “For her pioneering research and contributions to applications in bioleaching and metals remediation.” Dr. Brierley has a PhD in Environmental Sciences from the University of Texas (Dallas), a MS degree in Chemistry and a BS degree in Biology, the latter two degrees from New Mexico Institute of Mining and Technology.