Bacterial Leaching

Biotechnology in the Mining Industry

Preston Devasia and K A Natarajan

Bacterial leaching is the extraction of metals from their ores using microorganisms. Microbial technology offers an economic alternative for the mining industry, at a time when high-grade mineral resources are being depleted.

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Why Bacterial Leaching

Worldwide reserves of high-grade ores are diminishing at an alarming rate due to the rapid increase in the demand for metals. However there exist large stockpiles of low and lean grade ores yet to be mined. The problem is that the recovery of metals from low and lean grade ores using conventional techniques is very expensive due to high energy and capital inputs required. Another major problem is environmental costs due to the high level of pollution from these technologies. Environmental standards continue to stiffen, particularly regarding toxic wastes, so costs for ensuring environmental protection will continue to rise.

Biotechnology is regarded as one of the most promising and certainly the most revolutionary solution to these problems, compared to pyrometallurgy or chemical metallurgy. It holds the promise of dramatically reducing the capital costs. It also offers the opportunity to reduce environmental pollution. Biological processes are carried out under mild conditions, usually without addition of toxic chemicals. The products of biological processes end up in aqueous solution which is more amenable to containment and treatment than gaseous waste.

Microorganisms Involved

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Bioleaching, bioextractive metallurgy, biotechnology in mining.

Bacterial extraction of metals is not a new technology as it has been in application for ore leaching for centuries, though the mechanism remained unknown. Specifically copper was recov-

The most important player in the bioleaching process is *Acidithiobacillus ferrooxidans*. It is a chemoautotrophic acidophile, meaning that it obtains its energy from inorganic sources and fixes its own carbon while growing in acidic medium. Its unique ability to oxidise ferrous to ferric, and sulphur and reduced sulphur compounds to sulphuric acid, leads to leaching of metals from their oxide and sulphide ores.

ered by man as early as 1000 BC from metal laden waters which passed through copper ore deposits. Pioneering work was carried out by W Rudolfs and A Helbronner, S A Waksman and I S Joffe, and V Carpenter and L K Herndon on bacteria capable of oxidising sulphur compounds to sulphuric acid. This was followed by the isolation of the iron and sulphur oxidising bacteria, *Thiobacillus ferrooxidans* (now called *Acidithiobacillus ferrooxidans*), by A R Colmer and M E Hinkle in 1947, to lay the foundation for subsequent research into the role of microorganisms in leaching. A consortium of microorganisms namely *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, *Leptospirillum ferrooxidans*, *Sulpholobus* spp. and thermophilic bacteria including *Sulpholobus thermosulphidoxidans* and *Sulpholobus brierleyi* are known to be involved in bioleaching. Anaerobes would also be found in leaching areas.

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It must however be noted that a strong potential exists for biased sampling of microbial species from bioleaching habitats. Current techniques for the collection of microorgansims from bioleaching areas strongly favour the recovery of microbes that are more readily accesible, for example those in solution, rather than those that are more firmly adhered on the ore body and may be more important in bioleaching. Moreover, existing methods of cultivation of microorganisms in the laboratory do not permit the growth of some of the microorganisms from the habitat sampled. It is quite possible, that some of the species of bioleaching microorganisms are being underestimated or missed altogether due to these problems. A clear picture of the microbial diversity in a bioleaching habitat is required. This type of information is essential for the advancement of our understanding of microbial metal solubilisation in biomining applications.

There are two major mechanisms of bacterial leaching. One involves the ferric-ferrous cycle i.e. the indirect mechanism, whereas the other involves physical contact of the organism with the insoluble sulphide i.e. the direct mechanism.

Mechanisms

A generalised reaction can be used to express the biological oxidation of a mineral sulphide involved in leaching:

$$MS + 2O_2 \longrightarrow MSO_4,$$

where M is a bivalent metal.

There are two major mechanisms of bacterial leaching. One involves the ferric-ferrous cycle (indirect mechanism), whereas the other involves physical contact of the organism with the insoluble sulphide (direct mechanism) and is independent of the indirect mechanism. An important reaction mediated by *Acidithiobacillus ferrooxidans* is:

$$4FeSO_4 + O_2 + 2H_2SO_4 \longrightarrow 2Fe_2(SO_4)_3 + 2H_2O.$$

Ferric sulphate is a strong oxidising agent capable of dissolving a wide range of metal sulphide minerals. Leaching brought about by ferric sulphate is termed indirect leaching because it proceeds in the absence of both oxygen and viable bacteria. This mode is responsible for leaching several minerals:

$$CuFeS_2 \text{ (chalcopyrite)} + 2Fe_2(SO_4)_3 \longrightarrow CuSO_4 + 5FeSO_4 + 2S^0,$$

$$FeS_2 \text{ (pyrite)} + Fe_2(SO_4)_3 \longrightarrow 3FeSO_4 + 2S^0,$$

$$UO_2 + Fe_2(SO_4)_3 + 2H_2SO_4 \longrightarrow UO_2(SO_4)_{4\text{-}3} + 2FeSO_4 + 4H^+.$$

Elemental sulphur generated by indirect leaching can be

The two major techniques used in leaching are percolation and agitation leaching. Percolation leaching involves the percolation of a lixiviant through a static bed, whereas agitation leaching involves finer particles agitated in a lixiviant.

converted to sulphuric acid by *Acidithiobacillus ferrooxidans*:

$$2S^0 + 3O_2 + 2H_2O \longrightarrow 2H_2SO_4\,.$$

This sulphuric acid maintains the pH at levels favourable to the growth of bacteria and also helps in the effective leaching of oxide minerals:

$$CuO\ (\text{tenorite}) + 2H_2SO_4 \longrightarrow CuSO_4 + H_2O,$$
$$UO_3 + 3H_2SO_4 \longrightarrow UO_2(SO_4)_{4\text{-}3} + H_2O + 4H^+.$$

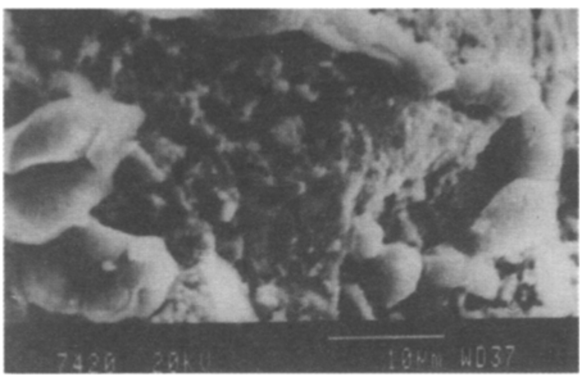
In the direct mechanism of leaching by bacteria, intimate contact and adhesion to the mineral takes place prior to enzymatic attack by the organism. The direct mechanism is inferred from scanning electron micrographs which demonstrate bacterial adhesion on mineral surfaces (*Figure* 1). The direct mechanism is further confirmed by the leaching of synthetic sulphides free of iron, where only the direct attack of the bacteria can lead to leaching:

$$CuS\ (\text{covellite}) + 2O_2 \longrightarrow CuSO_4\,,$$
$$ZnS\ (\text{sphalerite}) + 2O_2 \longrightarrow ZnSO_4\,.$$

Bacterial Leaching Techniques

The two major techniques used in leaching are percolation and agitation leaching. Percolation leaching involves the percolation of a lixiviant through a static bed, whereas agitation leaching involves finer particle sizes agitated in a lixiviant. Due to the large-scale operations involved in bacterial leaching, percolation leaching is preferred commercially.

Figure 1. Scanning electron micrograph of Thiobacillus ferrooxidans adhering to chalcopyrite.



The principal commercial methods are *in situ*, dump, heap and vat leaching. *In situ* leaching involves pumping of solution and air under pressure into a mine or into ore bodies made permeable by explosive charging. The resulting metal-enriched solutions are recovered through wells drilled below the ore body. Three types of ore bodies are generally considered for *in situ* leaching:

surface deposits above the water table, surface deposits below the water table and deep deposits below the water table.

Dump leaching involves uncrushed waste rock which is piled up. These dumps generally contain about 0.1-0.5% copper, too low to recover profitably by conventional procedures. Some of these dumps are huge, containing in excess of 10 million tons of waste rock. Heap leaching requires the preparation of the ore, primarily size reduction, so as to maximise mineral-lixiviant interaction and the laying of an impermeable base to prevent lixiviant loss and pollution of water bodies. Essentially, both dump and heap leaching involve the application of the lixiviant to the top of the dump or heap surface and the recovery of metal laden solution that seeps to the bottom by gravity flow. The dilute sulphuric acid sprinkled on top percolates down through the dump, lowering the pH and promoting the growth of acidophilic microorganisms. The acid run-off is collected at the bottom of the dump, from where it is pumped to a recovery station. Copper is extracted from the acid run-off by cementation or solvent extraction or electrowining. All the above processes are essentially uncontrolled from a biological and engineering stand point. Besides these processes are slow in nature and require long periods of time to recover a portion of the metal.

Biological copper leaching is practiced in many countries including Australia, Canada, Chile, Mexico, Peru, Russia and the United States of America. Copper recovery from bioleaching accounts for about 25% of the world copper production.

Vat leaching as currently applied to oxide ores involves the dissolution of crushed materials in a confined tank. More controls can be brought in for enhanced recovery by the use of bioreactors, though necessarily these involve higher costs. However for ore concentrates and precious metals they are being considered actively.

Bioleaching of Copper

Biological copper leaching is practiced in many countries including Australia, Canada, Chile, Mexico, Peru, Russia and the United States of America. Copper recovery from bioleaching accounts for about 25% of the world copper production. Following the initial isolation of *Acidithiobacillus ferrooxidans* from coalmine water in 1947, studies quickly disclosed its presence in

Figure 2. A view of the Malanjkhand Copper Mines, Madhya Pradesh, India.

copper-leaching operations. *Acidithiobacillus ferrooxidans* is also found in the Malanjkhand Copper Mines (*Figure* 2).

Iron- and sulphur-oxidising acidophilic bacteria are able to oxidise certain sulphidic ores containing encapsulated particles of elemental gold, resulting in improved accessiblity of gold to complexaton by leaching agents such as cyanide. Bio-oxidation of gold ores is a less costly, less polluting alternative to other oxidative pretreatments such as roasting and pressure oxidation.

The physical configurations of bioleaching operations worldwide for copper are mostly uniform. Typically, copper ore mined from open pits is segregated, higher-grade material is concentrated to produce feed for smelting, while the lower-grade ore is subjected to leaching. The ore is piled on an impermeable surface until a dump of suitable dimension forms. After the top is levelled, leach solution is flooded or sprayed onto the dump. A copper dump represents a complex and heterogenous microbiological habitat. It contains solids ranging in size from boulders to fine sand and includes material of complex mineralogy. Bacterial colonisation occurs mainly in the top one meter or so. The temperature may reach 90^{0}C in the interior of the dump and supports a range of thermophillic microorganism, which are often anaerobic, or microaerophilic. In these regions indirect leaching by ferric sulphate also prevails. The exterior of the dump is at ambient temperature and undergoes changes in temperature reflecting seasonal and diurnal fluctuations. Many different microorganisms have been isolated from copper dumps, some of which have been studied in the laboratory. These include a variety of mesophilic, aerobic iron and sulphur oxidising microorganisms; thermophilic iron and sulphur oxidising microorganisms; and anaerobic sulphate reducing bacteria. Some are heterotrophic bacteria, which indirectly affect metal solubilisation by affecting the growth and activity of metal solubilising bacteria. Others are protozoa, which interact with and prey on different types of bacteria.

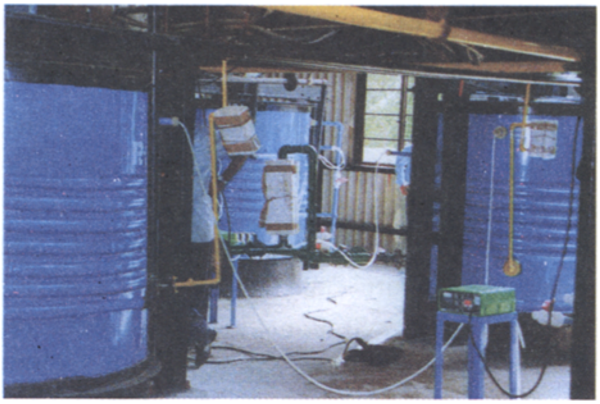


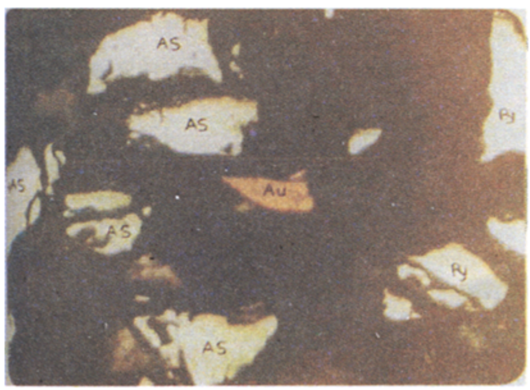
Figure 3. Demonstration bioreactor plant commissioned at Hutti Gold Mines, Karnataka.

Leach solutions enriched with copper exit at the base of the dump and are conveyed to a central recovery facility. In most large-scale operations the leach solution, containing 0.5-2.0 g copper per liter is pumped into large cementation units containing iron scrapings for cementation and then electrolysis. A typical large dump may have an operating life of over ten years.

Bioleaching of Uranium

Uranium leaching proceeds by the indirect mechanism as *Acidithiobacillus ferrooxidans* does not directly interact with uranium minerals. The role of *Acidithiobacillus ferrooxidans* in uranium leaching is the best example of the indirect mechanism. Bacterial activity is limited to oxidation of pyrite and ferrous iron. The process involves periodic spraying or flooding of worked-out stopes and tunnels of underground mines with lixiviant. Another method in use for uranium extraction is vat leaching. Bioleaching has also been used succesfully to obtain uranium from waste gold ore.

Figure 4. Mineralogical photograph of encapsulation of gold (Au) in pyrite (Py) and arsenopyrite (As).



Bioliberation of Gold

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Recently, bio-oxidation of gold ores has been implemented as a commercial process, and is under study worldwide for further application to refractory gold ores. Technology developed by K A Natarajan and co-workers at the Indian Institute of Science is being applied at the Hutti Gold Mines, Karnataka, India for extraction of gold (*Figure* 3). Bio-oxidation involves treatment with *Acidithiobacillus ferro-oxidans* to oxidise the sulphide matrix prior to cyanide extraction. Commercial exploitation has made use of heap leaching technology for refractory gold ores. Refractory sulphidic gold ores contain mainly two types of sulphides: pyrite and arsenopyrite. Since gold is usually finely disseminated in the sulphide matrix, the objective of biooxidation of refractory gold ores is to break the sulphide matrix by dissolution of pyrite and arsenopyrite (*Figure* 4).

Conclusion

Bacterial leaching is a revolutionary technique used to extract various metals from their ores. Traditional methods of extraction such as roasting and smelting are very energy intensive and require high concentration of elements in ores. Bacterial leaching is possible with low concentrations and requires little energy inputs. The process is environment friendly even while giving extraction yields of over 90%.

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Selected Reading

[1] R Acharya, Bacterial leaching: a potential for developing countries, *Genetic Engineering and Biotechnology Monitor*, Vol. 27, pp.57-58, 1990.
[2] H L Ehrlich, *Geomicrobiology*, 4th Ed. Marcel Dekker, New York, 2002.
[3] J Haddadin, C Dagot and M Fick, Models of bacterial leaching, *Enzyme and Microbial Technology*, Vol.17, pp.290-305, 1993.
[4] D E Rawlings, Heavy metal mining using microbes, *Annual Review of Microbiology*, Vol. 56, pp.65-91, 2002.