Present and future commercial applications of biohydrometallurgy

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Abstract

Modern commercial application of biohydrometallurgy for processing ores became reality in the 1950s with the advent of copper bioleaching at the Kennecott Copper Bingham Mine. Early application entailed dump leaching of low-grade, low-value, run-of-mine material. Dump bioleaching has evolved into a commercially accepted option for bioheap copper leaching of higher-grade, higher value ores. This commercial practice is exemplified by at least 11 mining operations. Paradoxically, application of biohydrometallurgy in the pretreatment of refractory gold ores began with processing high value concentrates, using biooxidation-tank processes and was followed by extension to processing low-grade, lower value ores in heaps. Now, bioleaching has been extended to the commercial extraction and recovery of cobalt. Even with the current success of biohydrometallurgical applications in the mining industry, the real potential of biotechnology in mining remains to be realized. As confidence in commercial bioprocessing grows and experience extends the application’s knowledge base, innovations and new commercial practices will emerge. Near-term future commercial applications will likely remain focused on recoveries of copper, gold and possibly nickel. Recent technical advances show that very refractory chalcopyrite can be successfully bioleached. Processes for copper recovery from this mineral will include both heap and stirred-tank reactors. Next generation technologies for pretreatment of refractory gold ores will be based on use of thermophilic bacteria for sulfide oxidation. For biohydrometallurgy to commercially advance, the microbiologist must work cooperatively with the practitioners of the technology for mutual understanding of operational limitations and practical constraints affecting the microbiological component. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Modern commercial application of biohydrometallurgy began with bioleaching of copper from sub-marginal-grade, run-of-mine material. Kennecott Copper has successfully used this process since the 1950s. Other mining operations around the world followed Kennecott’s lead. Today dump bioleaching remains a very low cost process for scavenging copper from rock that cannot be economically processed by any other method. Despite the commercial success of dump bioleaching, little effort has been expended to enhance the microbiological component of this leach process. Expansion of biohydrometallurgy into recovery of other metals did not occur until the mid-1980s when the first commercial plant for pretreatment of refractory gold bearing concentrate was commissioned at the Fairview operation in 1980.
South Africa. Now processes for copper bioleaching and refractory gold pretreatment are engineered with the microorganisms in mind to promote their activity. This paper reviews the current state of commercial applications of biohydrometallurgy, examines potential future developments, and portrays the role of the microbiologist in facilitating continued growth and commercial acceptance of the technology.

Predictions with regard to the future of commercial biohydrometallurgy applications were proffered at a 1986 workshop, “Biotechnology for the Mining, Metal-Refining and Fossil Fuel Process Industries” [1]. At the time, one author, J.F. Spisak [2], stated that biotechnical applications in the mining industry were in the “infancy” stage. Biohydrometallurgy was viewed as a 10–15-year undertaking for process development, practical design and field-testing. Spisak [2] stated that the greatest hurdles to microbial process application in the extractive industry were acceptance and commitment of funds by management. Technical feasibility was not considered a substantial impediment in 1986 [2]. Another speaker, V.I. Lakshmanan [3], at the same workshop had a similar prediction for the future of commercial biohydrometallurgy. He stated that development of biohydrometallurgy applications in the mining industry would be limited by the industry’s conservative attitude towards exploiting new technologies. Lakshmanan [3] predicted that acceptance will be slow and will depend on the vision and risk taking by senior management. The predictions of Spisak [2] and Lakshmanan [3] remain partially true today. However, there is an ever increasing acceptance by the senior management of many companies that biohydrometallurgy is an important commercial technology of the future, because of its simplicity, low cost and applicability to low-value ores. The commercial examples in this paper illustrate the expansion of microbial processing in the mining industry over the last 13 years.

2. Present applications

2.1. Copper extraction

Early commercial applications of bioleach technology processed submarginal grade copper-bearing rock in dumps. Recent applications of the technology use engineered bioleach heaps. All of these operations are in countries of the Southern Hemisphere. It is noteworthy that the pioneering work in North America was not advanced to commercial application. Eleven copper bioheap leach plants and one in situ bioleach operation have been commissioned since 1980 (Table 1) [4].

An excellent example of a current commercial bioleach application is the Quebrada Blanca operation in northern Chile [5]. This bioleach plant is located on the Alti Plano at an elevation of 4400 m, negating the criticism of some operators that the leaching bacteria cannot function under the cold temperatures and low oxygen partial pressure of high altitudes. At Quebrada Blanca 17,300 t/day of sulfide ore are crushed to 100% passing 9 mm, agglomerated with sulfuric acid and hot water and stacked to form 6–6.5 m high heaps. Bacterial activity is facilitated by aeration using an array of air lines installed beneath the heap and low pressure fans. Bacterial process monitoring includes on-site measurements of respiration. The Quebrada Blanca bioleach process illustrates the successful “evolution” of biohydrometallurgy in the mining industry. The plant design at Quebrada Blanca and other similar operations incorporates the bacterial requirements of the process. Research findings on improving bacterial activity are now applied in commercial operations.

Table 1

<table>
<thead>
<tr>
<th>Plant</th>
<th>Size (t/day)</th>
<th>Years in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lo Aguirre, Chile</td>
<td>16,000</td>
<td>1980–1996</td>
</tr>
<tr>
<td>Gunpowder’s Mammoth Mine, Australia</td>
<td>in situ*</td>
<td>1991–Present</td>
</tr>
<tr>
<td>Mt. Leyshon, Australia</td>
<td>1370</td>
<td>1992–in closure</td>
</tr>
<tr>
<td>Cerro Colorado, Chile</td>
<td>16,000</td>
<td>1993–Present</td>
</tr>
<tr>
<td>Girilambone, Australia</td>
<td>2000</td>
<td>1993–Present</td>
</tr>
<tr>
<td>Ivan-Zar, Chile</td>
<td>1500</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>3000</td>
<td>1996–Present</td>
</tr>
<tr>
<td>Cerro Verde, Peru</td>
<td>15,000</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 Project, Myanmar</td>
<td>15,000</td>
<td>1998–Present</td>
</tr>
</tbody>
</table>

* ≈ 1.2 million tonne ore body.
2.2. Refractory gold pretreatment

Seven plants have been commissioned for biooxidation pretreatment of sulfidic-refractory gold concentrates (Table 2) [4]. These plants use large, aerated, stirred-tank reactors for biooxidation of pyrite and arsenopyrite minerals locking the gold values. The Youanmi plant, currently closed due to low gold price coupled with high mining costs, employs the BacTech (Australia) technology, which uses a moderately thermophilic bacterial culture similar to *Sulfobacillus thermosulfidooxidans*. Biooxidation takes place at temperatures between 45°C and 55°C [6]. The other six sulfidic refractory, gold concentrate plants use the BIOX® process, which is a mixed culture of *Thiobacillus* and *Leptospirillum* operating at 40°C to about 45°C [7]. An eighth biooxidation plant at the Beaconsfield Mine, using combined BacTech and Mintek technology, is soon to be commissioned in Tasmania. Biooxidation pretreatment in tank reactors has only been commercially practiced for high value flotation concentrates. Whole-ore biooxidation generally cannot support the associated costs of power for aeration.

Biooxidation pretreatment of lower value, refractory, whole ores can be conducted in heaps, similar to those used for bioleaching of copper. This bioheap process has yet to be practiced on an ongoing commercial scale. However, Newmont Gold demonstrated the practicality of biooxidation-heaps pretreatment on large-scale demonstration heaps [8–10] and is now constructing a commercial scale plant. Biooxidation is carried out on ore crushed to about 12.7 mm. The heaps are ventilated and pretreatment is conducted for periods of 100 to as long as 270 days. The oxidized ore is then removed from a pretreatment pad, neutralized and leached. Gold recovery ranges from 60% to 80% of the contained value, depending on mineralogy and particle sized used. Biooxidation-heap pretreatment is generally considered when the ore is low-grade, economics cannot sustain the cost of making a concentrate, the mineralogy is such that the refractory sulfides cannot be concentrated, or the project is too small to support a high capital process.

The current shut down of the Youanmi biooxidation pretreatment plant and the delay in start-up of Newmont’s commercial biooxidation-heap pretreatment process reflect the sensitivity of these processes to gold prices. Even relatively low-cost, innovative biohydrometallurgical processes, such as biooxidation-heap leaching, require substantial capitalization for large-scale commercialization. Companies may not be willing to make this investment in periods of low metal value prices and will delay implementation until favorable economic conditions occur.

2.3. Cobalt bioleaching

The first commercial plant for bioleaching and recovery of cobalt has been commissioned. BRGM has commercialized a bioleach process for cobalt recovery for the Kasese Cobalt in Uganda. A cobaltiferous pyrite concentrate, grading 1.38% cobalt, was produced from the Kilembe Mine and stockpiled over the last 30 years. The stockpile contains 1.1 million dry-tons of about 80% pyrite. Bioleaching is conducted in the largest stirred tank reactors in operation using an inoculum of mesophilic iron-oxidizing bacteria. Three 1350 m³ (≈ 3.6 × 10⁵ gal) primary reactors and a single secondary reactor are used for bioleaching about 241 metric tons of concentrate per day at 20% pulp density. Reportedly, cobalt recovery is 92%. The flow sheet for cobalt recovery is complex requiring iron removal and separate recovery schemes for copper and zinc [11,12].

3. Future (potential) commercial applications

Prediction of future long-term commercial applications of biological processes in the metal extrac-

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Table 2: Commercial biooxidation plants treating flotation concentrates

<table>
<thead>
<tr>
<th>Plant</th>
<th>Size (t/day)</th>
<th>Years in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairview, South Africa</td>
<td>35</td>
<td>1986, 1991–Present^*</td>
</tr>
<tr>
<td>Sao Bento, Brazil</td>
<td>150</td>
<td>1990–Present</td>
</tr>
<tr>
<td>Wiluna, Australia</td>
<td>115</td>
<td>1993–Present</td>
</tr>
<tr>
<td>Ashanti, Ghana</td>
<td>1000</td>
<td>1994–Present</td>
</tr>
<tr>
<td>Youanmi, Australia</td>
<td>120</td>
<td>1994–1998</td>
</tr>
<tr>
<td>Tamborague, Peru</td>
<td>60</td>
<td>1999–Present</td>
</tr>
</tbody>
</table>

^The Fairview plant was commissioned in 1986 and expanded in 1991 to 35 t/day.
tion industry is risky at best, and foolhardy at worst. Nevertheless, it is almost certain that some of today’s research will lead to innovative processes for commercial application. The reason is because biohydrometallurgy offers advantages—operational simplicity, low capital and operating cost and shorter construction times—that no other alternative process can provide. This section focuses on near-term commercial developments. Also, some specific needs and potential benefits for commercialization of recent biohydrometallurgical advances are presented.

3.1. Copper extraction

In the near future, stirred-tank bioleaching of chalcopyrite concentrates will be a commercial reality. A year-long pilot trial at Copper Mines of Australia’s Mt. Lyell operation in Tasmania has demonstrated the technical and commercial viability of using moderately thermophilic bacteria to leach a finely ground concentrate and recover the solubilized copper with solvent extraction-electrowinning [13].

Another commercial approach to chalcopyrite concentrate leaching is the use of bacterially generated ferric iron. A high concentration of ferric iron is produced in a separate reactor, heated to about 70°C, and the ferric solution is contacted with the chalcopyrite concentrate [14]. Ferric leaching offers several advantages over complete oxidation of chalcopyrite. Copper recoveries in the high 90% range are achieved, especially when the chalcopyrite is finely ground. The sulfur moiety of chalcopyrite is oxidized to elemental sulfur, not sulfuric acid, which significantly reduces downstream neutralization costs and the sulfur may be a saleable product. Operating costs are greatly minimized because less air is required to oxidize ferrous iron than to oxidize chalcopyrite. Ferric iron leaching of chalcopyrite does require further development before it is commercially applied. One issue is the cost associated with heating the ferric solution before contact with the concentrate and cooling the ferrous-containing liquor before recirculation to the bacterial reactor. Thermophilic bacterial generation of the ferric iron solution may be an answer. Also, some equipment development is required to improve the contact between the chalcopyrite concentrate and the ferric solution.

Commercial innovations in bioheap leaching of chalcopyrite ore are very likely given the success in chalcopyrite concentrate bioleaching. Validation of the microbial and chemical conditions enhancing copper dissolution from chalcopyrite and minimizing passivation layers have stimulated developments of this technology [15]. It is probable that some of the operational parameters developed for chalcopyrite ore bioheap leaching can be economically applied to the dump leaching of run-of-mine primary copper minerals. Incremental improvements in copper recoveries from dump operations that bioleach up to a billion tons of rock would be significant.

The predominant microbial system for research, process development and commercial application has been the members of the genus *Thiobacillus*, and *T. ferrooxidans* in particular. Recently, the *Leptospirillum* have been included in the stable of useful microorganisms. Future process developments will and must include thermophilic bacteria that will have an increasingly important role in biooxidation of minerals [16,17]. Thermophilic *Archaeae, Sulfolobus* species, *Acidianus brierleyi* and *Metallosphaera sedula*, which grow at 60°C to 75°C, are particularly adept in bioleaching of copper from the highly refractory chalcopyrite. Recent published reports reflect the growing interest in fundamental and practical application studies of thermophilic microorganisms for bioleaching. [18–23].

3.2. Refractory gold pretreatment

Commercial demonstration of the biooxidation-heap technology for pretreatment of low grade refractory sulfidic gold ores revealed the propensity for the internal portions of the heap to reach temperatures of 60°C to 75°C [24]. Heating occurs with 2–3% sulfide-sulfur content, as pyrite. The massive size of the biooxidation-heaps precludes temperature control. The high temperatures necessitate the use of thermophiles that can function from 45°C (*Sulfobacillus* species) to over 70°C (the *Archaea* discussed above). Mixed cultures of mesophilic and thermophilic mineral oxidizing bacteria will be used for inoculation of the heap systems. The mixed culture inocula will provide the appropriate bacteria over the temperature ranges as the oxidation of the pyrite heats the bioheap.
Successful operation of Mt. Leyshon indicates a potential for future biooxidation pretreatment of refractory gold ore in the presence of copper sulfide minerals [25]. Copper acts as a cyanicide, increasing reagent consumption to the point that the process becomes uneconomic. Bioleaching can be used to leach the copper from the ore concurrent with oxidative pretreatment of refractory gold sulfides. The copper is removed and the gold can be leached with cyanide at a significantly reduced consumption level. This combined bioleach-biooxidation process can be used for both recovery of copper and gold from ores that could not be otherwise processed.

Another innovative process for biooxidation of refractory gold ores combines the concept of the biooxidation-heap with pretreatment of flotation concentrates [26]. This technology, developed by Geobiotics, is called GEOCOAT™ and is currently being pilot tested. The process entails coating refractory sulfide gold concentrates onto a screened support rock or ore. Biooxidation pretreatment takes place in a stacked heap configuration. The oxidized concentrate is removed from the support rock for gold extraction by conventional metallurgical processes. If the support rock is also a refractory ore, this can also be leached following biooxidation to recover additional gold values. The GEOCOAT™ process has also been tested for bioleaching copper from chalcopyrite concentrate using thermophilic microorganisms [27]. This technology offers a less expensive process option for concentrate pretreatment and can be used for concurrent biooxidation of high value concentrates and low value ores. Further development of the GEOCOAT™ technologies may depend on other research and development centers as this technology is currently for sale by Geobiotics.

3.3. Recovery of other metals

Biohydrometallurgy is now applied on a commercial scale for leaching of copper and pretreatment of refractory gold ores and concentrates. The utility of bioleaching for uranium has also been demonstrated on a large-scale [28]. There is considerable potential for bioleaching and biobeneficiation (pretreatment) of a wide range of base-metal and platinum-group metals [29]. Microbially leaching has been shown at bench scale for the base metal sulfides of Co, Ga, Mo, Ni, Zn and Pb. Sulfide minerals occluding platinum-group metals (Pt, Rh, Ru, Pd, Os and Ir) can be microbially pretreated.

Billiton has developed the BioNIC® process as a biohydrometallurgical technology for extraction of nickel from low-grade sulfide ores [30]. This technology is based on Goldfields BIOX® process for biooxidation pretreatment of refractory gold concentrates. Pilot plant testing has demonstrated the efficacy of a mixed culture of T. ferrooxidans, T. thiooxidans and L. ferrooxidans in bioleaching of nickel from pentlandite in a complex sulfide concentrate. The bioleaching portion of the process is successful, but commercialization will also depend on selective recovery of the nickel from the leach solution. This latter aspect appears to be possible using conventional metallurgical procedures of ion exchange or solvent extraction. The biotechnologist must be aware that a demonstrated effect of the microorganisms is only a part of a commercial process and all must come together with favorable economics before a plant can be built. The next commercial application of base-metal bioleaching appears to be for nickel. The promising developments in bioleaching of cobalt and nickel portend commercialization of biohydrometallurgical processing of base metals other than copper.

3.4. Opportunities for the technologist

There are several specific needs for advancing the commercialization of biohydrometallurgy. These needs can be met by research in applied microbiology. In most instances, these advancements will require an iterative relationship with the metallurgical engineers to maximize understanding of operational needs and to help the engineers understand the role and requirements of the microorganisms in their operations.

One fertile area for additional research is a comprehensive study of the microbial composition of both bioheap systems and stirred-tank reactors. A heterogeneous and complex microflora, composed of both acidophilic heterotrophic and autotrophic microorganisms, exist with commercial bioprocessing systems. The dynamics of the microbial population also change with time and conditions in the bioprocessing system. There is a need to both define and
understand the potential interactions among the components of the microflora. This has the potential for improving bioleaching and mineral biooxidation through definition of how the components of the system interact to bring about bioleach processes.

Rapid, accurate and simple techniques for monitoring the microbial activity in bioleach/mineral-biooxidation systems are needed for control of these processes by operators. How can a biological process occurring within a very large mass of rock be monitored with procedures used by commercial operators, who are unlikely to be microbiologists?

Stirred-tank bioreactors have clearly opened new opportunities for processing precious- and base-metal concentrates. However, the existing stirred-tank reactor design is relatively inefficient when it comes to aeration. Improved aeration designs will vastly improve the economics of stirred-tank reactors [31,32]. New types of reactors, for example, vat-type systems, that allow bioleaching and effective handling of whole ore particles in the 10-mesh size range are needed. Another area for development is in reactor materials of construction. New materials for high temperature, highly corrosive conditions that are of relatively low cost, would also advance the technology. Such reactors would amplify opportunities to bioleach whole ores.

4. Summary

Since the mid-1980s, there has been genuine growth in commercialization of bioleaching metals and biooxidation pretreatment of refractory gold concentrates. Refs. [1] and [33–44] review the progress in research and applications. Commercialization reflects the realization by mining management that biohydrometallurgical processes are robust and economically viable. Yet, embracing biotechnological applications, particularly in an economic climate of low metal prices, carries some risk. Although biohydrometallurgical processes can more than compete cost-wise with conventional metallurgical processes, there is still a capital investment for new operations. The decision-makers in the mining industry have to understand the technology and take the “risk” of implementing innovative technologies [45].

References


