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BACTERIAL LEACHING AS A PRE-TREATMENT STEP FOR GOLD RECOVERY FROM REFRACTORY ORES

In this article, pre-treatment such as bio-leaching before cyanidation is discussed as an alternative technique to treat refractory gold ores containing pyrite and arsenopyrite. There are two methods of bacterial leaching, namely stirred reactor bio-leaching and bio-heap leach processes. The examples of industrial applications and economics of bacterial leaching are given in detail.

INTRODUCTION

It is known that many of the gold and silver deposits are often associated with sulphide minerals, especially pyrite and arsenopyrite. Some of the precious metals in such ores are often found as very finely disseminated particles in the sulfide matrix. The encapsulation of precious metal particles in this manner makes their direct extraction by cyanidation is very difficult, as these metals are inaccessible to leaching solutions. Such ores are known as *refractory ores* (Attia and El-Zeky, 1989).

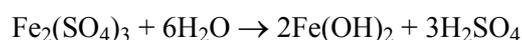
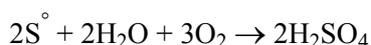
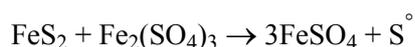
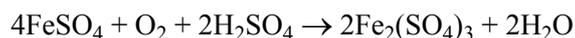
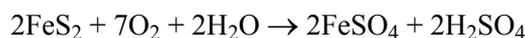
Various pre-oxidation methods of refractory ores and concentrates are commonly used to improve precious metal recoveries. For example, oxidative roasting has been used in some cases as a pre-oxidation step before cyanidation. Roasting removes harmful constituents by oxidation or volatilization, and liberates gold from pyrite or arsenopyrite. In some cases, however, this method of pre-oxidation can result in poorer metal recovery, particularly of silver, due to fusion and the formation of clinker, and solid compounds which consume cyanide in the subsequent metal recovery stage. Difficulties in compliance with environmental pollution regulations may also be encountered (Lawrence and Bruynesteyn, 1983).

An alternative and effective technique for treating such refractory ores is bio-leaching before cyanidation. This leaching process decomposes the sulfide matrix, thus exposing the encapsulated precious metals to leaching solution. Several investigators have advocated the use of *Thiobacillus ferrooxidans* bacteria for bio-leaching of sulfide ores or concentrates before leaching of gold with cyanide solutions.

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Bio-leaching is inexpensive in terms of investment costs, but it is also a slow process. Therefore, the operating costs are expected rather high (Lawrence and Bruynesteyn, 1983; Lawrence, 1994).

Bacterial leaching is fundamentally a natural process which is the result of a variety of bacteria oxidizing sulphide host minerals to liberate metal values. In the case of pyrite, the following equations describe the typical reactions that occur in a bacterically-catalyzed oxidation system (Gilbert et al., 1988; Demopoulos and Papangelakis, 1989).



MATERIALS AND METHODS

Thiobacillus ferrooxidans is the most common bacteria used for oxidation of sulfide ores before cyanidation (Attia and El-Zeky 1989; Lawrence, 1994; Brewis, 1995; Holmes, 1988). *Thiobacillus ferrooxidans* has a cell size in the range of 0.5 to 0.6 μm long. Its energy sources are ferrous iron and reduced sulfur. It will oxidize virtually all known sulphide minerals, including pyrite, arsenopyrite, copper sulphides etc. It thrives in the pH range 1.0 to 6.0, the optimum pH for maximum growth rate being between 2.0 to 2.5. Similarly, it survives in the temperature range 2 $^\circ\text{C}$ to 40 $^\circ\text{C}$, but its maximum efficiency was found within the range of 28–35 $^\circ\text{C}$ (Brewis, 1995). This bacteria are robust, thriving in H_2SO_4 environments at pH less than 2.5 with high dissolved-metal concentrations, e.g. 70 g/l iron, more than 15 g/l copper, and up to 30 g/l arsenic. None of these bacteria has been found to cause plant or animal diseases. The composition of nutrient solution is given in Table 1.

Table 1. Composition of the nutrient solution (Dogan, 1986)

| Compound | Grams |
|--|-----------------------------------|
| $(\text{NH}_4)_2\text{SO}_4$ | 0.15 |
| KCl | 0.05 |
| $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ | 0.50 |
| K_2HPO_4 | 0.05 |
| $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ | 0.01 + distilled water to 1000 ml |

The testing of bacterial leaching has the objective of optimizing four parameters:

1. The optimum particle size of solid for bacterial leaching is not standard for all ores and concentrates, and has to be established experimentally. Current practice seems to favor grinding to less than 35 μm in particle size.

2. The solid concentration in the pulp on which bacterial leaching is performed has been reported as a critical parameter, more influential than even the particle-size distribution of the feed. Maximum bacterial leaching rates of sulfide minerals have been reported to occur of 15% to 20% solids concentrations. Excessive sulfide material concentrations in the pulp may cause very significant reduction in the growth of bacteria and in the leaching rate, even to the extent of completely stopping oxidation of the mineral. Furthermore, the increasing concentration of sulfide minerals deteriorates the chemical conditions in the leaching system. The microorganisms present in the leach may be inadequate to maintain optimum leaching conditions at certain sulfide concentrations.

3. The optimization of nutrient addition should be established during the laboratory examinations. Small amounts of potassium, phosphorus, and nitrogen are required in solution to maintain bacterial activity and population growth. Additions of potassium hydrogen phosphate and ammonium sulfate should be optimized experimentally.

4. Aeration at relatively low flow rates (0.5–1.0 l/min, per liter of a slurry) has been reported as adequate to maintain the oxidation rate and bacterial growth. A temperature of around 35 °C has to be maintained for optimum bacterial activity and growth, as already mentioned. In industrial-scale operations, the bacterial leaching reactors have to be equipped with cooling coil systems in order to maintain the operating temperature in the optimum range (Yannopoulos, 1991).

DESCRIPTION OF THE LEACHING PROCESS

There are two general methods of bacterial leaching in gold hydrometallurgy. These are both stirred reactor bio-leaching process and bio-heap leach process. This article will focus upon the stirred reactor bio-leaching process.

Stirred reactor bio-leaching process

An important feature of bio-leaching as applied to refractory gold ores is the distinction that can be exploited between the relative reaction rates of gold-bearing sulphides. Unlike roasting and pressure leaching, which achieve rapid and total sulphide oxidation, bio-leaching is rather a slowly process. If the gold in a sulphidic ore or concentrate is predominantly disseminated in arsenopyrite, the more reactive arsenopyrite is preferentially oxidized than the pyrite. Consequently, liberated gold

becomes available for recovery without the need to oxidize all of the sulphur. Since capital and operating costs are directly related to the amount of sulphur that has to be oxidized to liberate gold, preferential oxidation of the gold-bearing sulphides can make the bacterial process more attractive when compared with its alternatives.

A simplified schematic flowsheet representing the bio-leaching process for sulphide concentrates is shown in Figure 1. The key components of the process involve concentration of a ground ore, usually by flotation, followed by oxidation of the gold-bearing sulphides to the required extent in a multi-stage process. Oxidized solids discharged from the last reactor are separated from the bio-leachate, washed and cyanide leached for gold extraction in a conventional CIP or other cyanidation circuit. The bio-leachate, usually containing primarily soluble iron and arsenic in addition to acid, is treated by controlled lime neutralization to produce stable precipitates for disposal.

Oxidation of the sulphide minerals in the bio-leach reactors is dependent on bacterial population growth and activity which are maintained at optimum process parameters through control of temperature, pH, redox potential, oxygen and carbon dioxide concentrations in the gas and liquid phases, supply of other bacterial nutrients, soluble metal concentrations, and retention times in the reactors (Lawrence, 1994).

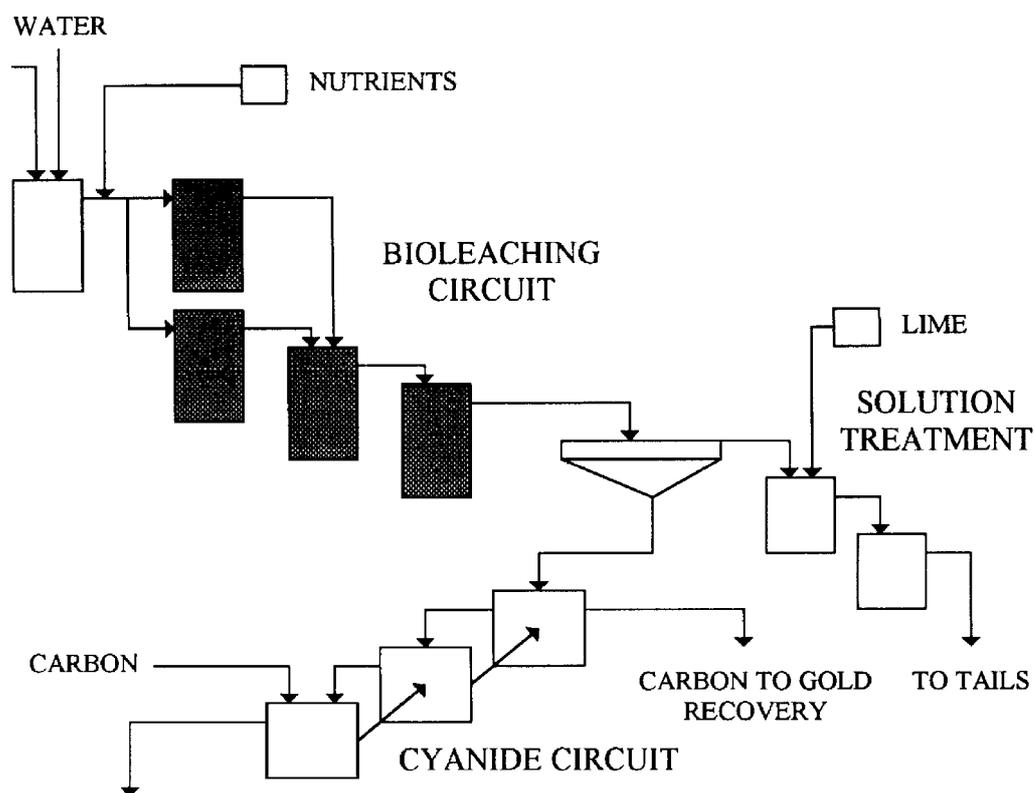


Fig. 1. Simplified flowsheet of the bio-leaching process (Lawrence, 1994)

Bio-heap leach process

This method involves crushing the ore, stacking the ore on lined pads and applying a dilute acid solution containing bacteria (usually *Thiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*). When sufficient sulphide has been oxidized to expose the gold, the ore heap is washed with water to remove acid and metals. Lime is subsequently added to increase the pH and the ore is then treated with cyanide solution. Since the ore to be bio-oxidized in heap-leach configuration is quite coarse, usually > 6.5 mm, the percent gold recovery is remarkably lower than would be achieved in stirred reactors. Bio-heap leaching is, therefore, generally considered when the ore is very low-grade and economics can not sustain the cost of making a concentrate or the mineralogy is such that the ore cannot be concentrated.

The bio-heap leach process, involving a bacterial culture suspended in acidified aqueous solution and nutrients (phosphorus and nitrogen) with crushed ore as it is stacked on a prepared pad, results in rapid and efficient bio-leaching. Ores need not remain on prepared pads for long time periods (60–90 days is a common leaching time) to achieve acceptable levels of sulphide oxidation and subsequent gold recovery. Sulphidic material with as little as 0.7 g/t of gold content can be profitably bio-heap leached with 60–70% gold recovery. Industry estimates place bio-heap leaching costs at \$(4–6)/t of ore processed (Brierley, 1995).

Industrial applications

Six bio-leaching plants have already been built but five plants are in operation. In all cases, BIOX technology of Biomin Technologies, South Africa, is used under license. The six commercial bio-leaching plants are listed in Table 2.

Table 2. Commercial bio-leaching plants (Lawrence, 1994; Brierley, 1995)

| Plant | Capacity, mt/d | Operating history |
|---------------------------|----------------|-------------------|
| Fairview, South Africa | 40 | 1986–present |
| Harbour Lights, Australia | 40 | 1992–1994 |
| Wiluna, Australia | 115 | 1993–present |
| Youanmi, Australia | 120 | 1994–present |
| Sao Bento, Brazil | 150 | 1990–present |
| Ashanti, Ghana | 720 | 1994–present |

Sao Bento Plant

The Sao Bento Plant shown in Table 2 is worthy of extra note because it combines a bio-leaching plant and pressure leaching plant to carry out the sulphide oxidation. Figure 2 provides a schematic flowsheet of this arrangement. The refractory concentrate is first passed through a single stage bio-leaching reactor, designed to provide 30% of the sulphur oxidation. The partially oxidized residue, following solid/liquid separation is then fully oxidized in a pressure autoclave. The bio-leaching step was added to the circuit not only to increase plant capacity but also to improve the performance of autoclave process by oxidation of pyrrhotite (the presence of pyrrhotite results in deleterious elemental sulphur formation in the autoclave), but also to decompose siderite FeCO_3 , which forms CO_2 and thus lowers the O_2 partial pressure in the autoclave (Lawrence, 1994; Slabbert et al., 1992).

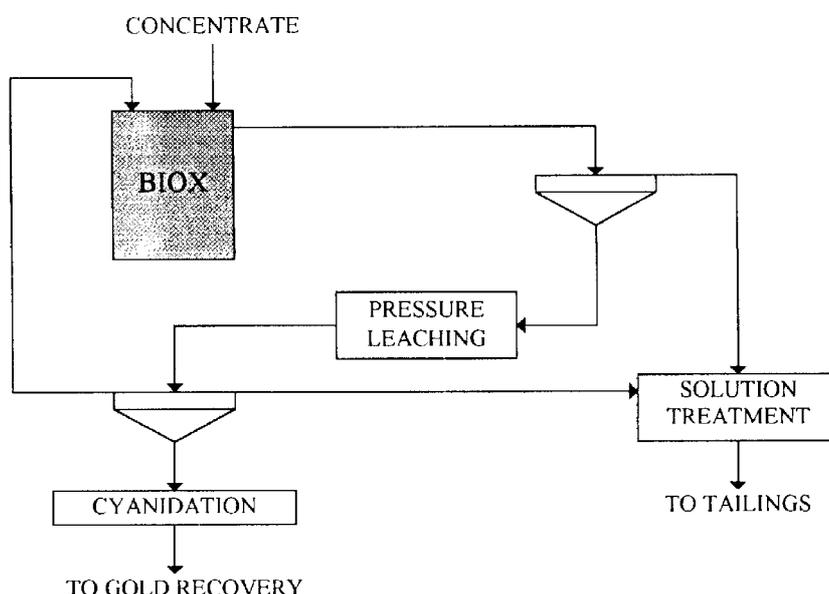


Fig. 2. Combination of bio-leaching and pressure leaching at Sao Bento Plant (Lawrence, 1994)

Fairview Plant

The bulk of the proven ore reserves in Fairview Mine are sulfidic and refractory. The main minerals are pyrite and arsenopyrite with trace amounts of chalcopyrite, sphalerite, stibnite, galena, pyrrhotite and pentlandite. The metallurgical operations at Fairview comprise a typical refractory gold processing plant treating the sulfidic ore body, a second plant treating the quartzitic ore, a flotation tailings treatment plant and

an arsenic refining plant. Typical ore and concentrate analyses for Fairview ore are depicted in Table 3.

The BIOX leaching plant currently treats from 40% to 60% of the Fairview Mine flotation concentrate. The remaining concentrate is treated by a roaster.

Temperature has been one of the most important controlling variables at Fairview plant and, as can be observed, has been held at 40 °C by cooling. Since 1984 pulp residence time and L/S ratio (liquid/solid ratio) were slowly lowered in order to improve the capacity of the leaching plant. Table 4 indicates the changes that have been made at both the pilot plant and the Fairview full scale plant.

Table 3. Ore and concentrate analyses (Van Aswegen et al., 1991)

| | Gold, g/t | Sulphur, % | Arsenic, % |
|-----------------|-----------|------------|------------|
| Run-of-mine ore | 7.0 | 0.6 | 0.3 |
| Concentrate | 109.0 | 23.0 | 4.5 |

Table 4. BIOX retention times (Van Aswegen et al., 1991)

| | Pilot Plant | | | | Fairview Plant | |
|--------------------------------------|-------------|------|------|-----|----------------|-----|
| | | | | | | |
| Retention, days | 10 | 4 | 4 | 3 | 4 | 4 |
| L/S ratio | 8/1 | 8/1 | 4/1 | 4/1 | 8/1 | 4/1 |
| kg ore/m ³ plant per 24 h | 10 | 30 | 60 | 75 | 30 | 50 |
| Gold dissolution, % | 97.0 | 96.8 | 96.8 | 93 | 92 | 95 |
| Sulphide oxidation, % | 97.4 | 84.4 | 84.8 | 72 | 90 | 92 |

On-going studies on nutrient addition has led to considerable reagent savings on the Fairview BIOX plant. The optimum conditions are still to be determined. Table 5 gives changes that have been brought about. The nutrients are conveniently provided as (NH₄)₂SO₄, KOH and H₃PO₄. Alternative sources of nutritious component include K₂SO₄ and (NH₄)₃PO₄.

Table 5. Nutrient addition at Fairview BIOX Plant (van Aswegen et al., 1991)

| | Addition rate, kg/t concentrate | | |
|-------------------------------|---------------------------------|------|------|
| | 1987 | 1988 | 1989 |
| NH ₄ ⁺ | 9.62 | 8.73 | 8.40 |
| K ⁺ | 13.05 | 4.27 | 1.43 |
| PO ₄ ³⁻ | 1.50 | 1.52 | 1.56 |

Economics of bacterial leaching

An estimated one-third of the world's total gold production is now originated from refractory deposits. Bio-leaching is a cost effective, efficient, safe, and environmentally friendly way to treat refractory gold concentrates and ores. Compared to roasting, bio-leaching can generally reduce capital costs by 12–20%, operating costs by 10% in some cases, and construction time by 25%. Gold recoveries increased by 2–13% as a result of bio-leaching.

If the gold grade is high enough, an autoclave leaching process can be effectively used to oxidize the sulphide minerals and exposing gold for cyanide leaching. Pressure leaching autoclaves are capital intensive because of their advanced materials of construction and need for an oxygen plant. The high level of operator training and skill necessary, and increased safety requirements to handle the high pressures and temperatures increase operating costs of this process. In spite of these remarks, the predominant number of American refractory plants successfully utilizes the pressure leaching as a pre-treatment operation before the cyanidation.

Comparisons of bio-leaching and roasting in terms of their technical and economical effectiveness were conducted by Wiluna Mines Ltd. and Ashanti Goldfields Ltd. The factors favouring the selection of bio-leaching for the Wiluna mine and for Ashanti's Sansu project are summarised in Table 6.

Table 6. Advantages of bio-leaching over roasting at Wiluna and Ashanti (Brierley, 1995)

| Criterion | Wiluna | Ashanti |
|-------------------|--------------|----------------|
| Capital cost | 12–16% less | 20% less |
| Operating cost | 8–10% less | 25% less |
| Gold recovery | 2–3% greater | 11–13% greater |
| Construction time | 25% less | Not available |

Comparisons of capital and operating cost of pre-treatment methods are given in Table 7.

Table 7. Economical analysis of pre-treatment methods (Corrans et al., 1993)

| | Roasting | Pressure leaching | Bacterial leaching |
|----------------|----------|-------------------|--------------------|
| Capital cost | 0.90 | 1.00 | 0.60 |
| Operating cost | 0.75 | 1.00 | 0.90 |

CONCLUSIONS

In spite of numerous advantages of bacterial leaching, it is currently the process of choice for only 20% of the refractory gold treatment plants worldwide. Equally remarkable is the recent commercialization of high-temperature minerals bio-leaching in moderately saline waters, a development that can further decrease capital and operating costs and increase commercial applications. Innovations in progress are bio-leaching at extreme temperatures (higher than 60 °C) and bio-degradation of highly refractory base-metal-sulphide minerals, such as chalcopyrite. Success in these applications promises to extend the utilization of bacterial leaching, increase in leaching efficiency, and enhance competitiveness of the technology.

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Omówiono bioługowanie jako alternatywną technikę przerobu trudno ługowanych rud złota zawierających obok złota piryt i arsenopiryt. Istnieją dwie metody ługowania bakteryjnego, a mianowicie

ługowanie w reaktorze z mieszaniem oraz ługowanie na hałdzie. Szczegółowe opisano przykłady przemysłowego zastosowania ługowania bakteryjnego i jego ekonomikę.