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BACTERIAL LEACHING OF COPPER ORES - THE CHILEAN EXPERIENCE*

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ABSTRACT

About 30% of the chilean copper reserves, estimated in more than 200 million tons of fine copper, are contained in materials such as waste, tailings and low grade ores, which are not economical to process by the conventional pyrometallurgical routes. Bacterial leaching processes pose a concrete alternative for the economical treatment of an important proportion of these materials and several industrial operations based on that technology are already runing in the country. In addition, the prospects of large supplies of locally produced, low price, sulfuric acid in the near future, contributes to make this process increasingly more attractive from an economic perspective.

A wide R&D local program supported by government agencies, PNUD/UNIDO development programs and the local copper industry, combines the efforts of universities, research centers and industry towards the aim of improving the efficiency of bacterial leaching processes and increase their scope of application in the local mining industry. It is expected that in a few years over 10% of the chilean copper will be produced based on bioleaching technologies.

INTRODUCTION

With an output of over one million ton anually (1.399 million ton in 1986), Chile is the world largest copper producer, accounting for over 15% of the world's copper output (1). About 80% of the Chilean copper is produced by Codelco, Chile's National Copper Corporation, a state enterprise which owns and operates the four largest chilean copper mines: Chuquicamata, El Teniente, El Salvador and Andina. Five privately-owned mines account for another 14% of the production: Mantos Blancos (Anglo-American), Los Bronces and El Soldado (Disputada), Las Cascadas and Lo Aguirre (Pudahuel), being the rest produced by several small mining companies (1).

Chilean copper industry is largely based on the exploitation of local porfidic sulfide ores which are processed according to the conventional pyrometallurgical route involving concentration, smelting and refining. Chilean copper reserves have been estimated at 200 million ton, wich represent 20% of the world reserves (1). However it is estimated that 30% of this copper is contained in materials such as waste, tailings or low grade ores, which are not economic to process by the current technology. As the chilean copper industry has grown so has its waste which has accumulated over the years at ever-increasing rates with the continuous decrease in the copper content of the ores. Bacterial leaching is at the moment the only adecuate technology for the economical recovery of the copper contained in these resources and there is a strong local interest to increase its application in the local mining industry.

Bacterial leaching is a natural occurring process whereby certain microorganisms, notably Thiobacillus ferrooxidans, catalyze the conversion of normally insoluble sulphide minerals into water soluble forms, thus freeing the associated metal ions for subsequent recovery. Typical reactions involved in the leaching of an ore containing, say chalcopyrite ($CuFeS_2$) and pyrite (FeS_2), are as follows:

$$2FeSO_4 + 0.5O_2 + H_2SO_4 \xrightarrow{\text{bacteria}} Fe_2(SO_4)_3 + H_2O \qquad \text{Ec.1}$$

$$CuFeS_2 + 2Fe_2(SO_4)_3 \longrightarrow CuSO_4 + 5FeSO_4 + 2S \qquad \text{Ec.2}$$

$$FeS_2 + Fe_2(SO_4)_3 \longrightarrow 3FeSO_4 + 2S \qquad \text{Ec.3}$$

$$2CuFeS_2 + 8.5O_2 + H_2SO_4 \xrightarrow{\text{bacteria}} 2CuSO_4 + Fe_2(SO_4)_3 + H_2O \qquad \text{Ec.4}$$

$$FeS_2 + 3.5O_2 + H_2O \xrightarrow{\text{bacteria}} FeSO_4 + H_2SO_4 \qquad \text{Ec.5}$$

$$S + 1.5O_2 + H_2O \xrightarrow{\text{bacteria}} H_2SO_4 \qquad \text{Ec.6}$$

The bacteria obtain the energy they need for functioning and growth from the oxidation of inorganic compounds of iron and sulfur. Thiobacillus ferrooxidans can enhance the dissolution of the present sulfides either by catalyzing the oxidation of ferrous iron in solution (Ec.1) leading to indirect dissolution of sulfides by ferric iron (Ecs.2,3), or by directly attacking the sulfides or any sulfide subproduct formed during the process (2)(Ecs.4,5). Bacterial action also contributes to maintain the acidic conditions in solution by catalyzing the oxidation of pyrite and by-produced sulfur (Ecs.5,6). Industrial practice of bacterial leaching involves the treatment of the ore under different configurations such as heaps, dumps, in-situ or in-place, whereby copper is extracted through periodical irrigation with sulfuric acid solutions. Copper is then precipitated with scrap iron or delivered as cathodes via solvent extraction-electrowining (3). A general scheme of the process is shown in Figure 1.

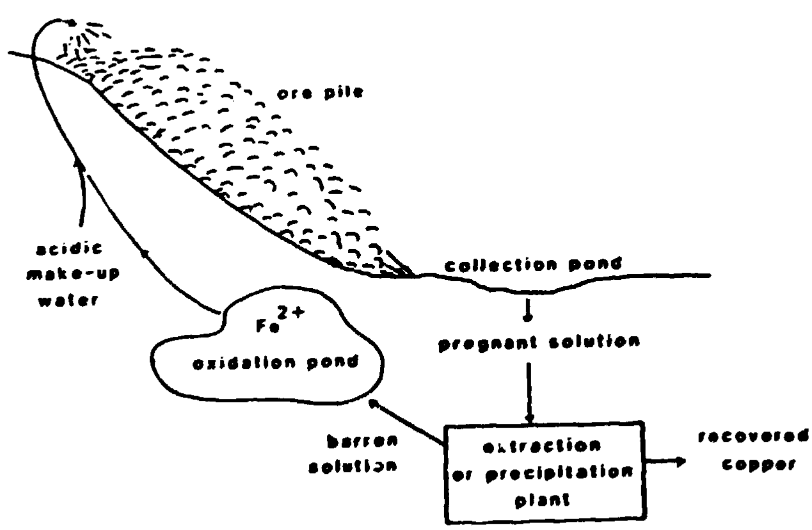

FIGURE 1. General flow-sheet of a bacterial leaching operation.

Since bacteria are living organisms, they require specific conditions for their best functioning and growth. Thiobacillus ferrooxidans in particular require abundant oxygen, a highly acid pH range (1.5-2.5), specific nutrients and a moderate temperature range (10-40° C) while some ions, for instance arsenic, molybdenum, mercury or chlorides, can be toxic to certain strains if they reach important concentrations. Similary, the characteristics of the system to be leached - the ore granulometry, mineralogy, dump porosity, air updraught, temperature profile, etc., will also affect the efficiency of the biological reactions and thus the amount and rate at which the metal can be recovered.

There is a wide-ranging set of design and operation parameters which provide the scope for optimizing bacterial leaching processes for economic benefits. There is no precedent in the industrialized countries about optimized bacterial leaching operations. There are no general models upon which the developing countries can design their leaching operations and, as a sources or technological know-how in this field, the potential of the industrialized countries, although important, is limited (4). In this situation, chilean engineers, technologists and scientists have taken the task of developing and applying this technology based mainly on the use of local human and technical resources. Some important industrial bacterial leaching operations are already running in the country and the potential minerals resources suitable to be processed following this route, are being assessed. More recently, a wide local effort on R&D in bioleaching technologies was started, which should help in providing a more scientific base for the design and control of the local bacterial leaching operations.

The general features of the chilean experience in the bacterial leaching of copper ores are now described, outlining the main local industrial and technological achievements in the field.

INDUSTRIAL ASPECTS.

Projects and resources.

Chuquicamata, the largest open pit copper mine in the world, produces more than half a million ton of fine copper annually (1). The exploitation of Chuquicamata has generated large amounts of overburden which have been estimated at about 1.000 millions ton with 0.2 to 0.3% average copper, being chalcopyrite and pyrite the main minerals present (5). In 20 years a similar reserve of copper will be generated. Results obtained from an experimental program on the bacterial leaching of the low grade ores accumulated in Chuquicamata dumps, have demonstrated the technical and economical feasibility of applying this process to recover the copper contained in these dumps (6). Leaching experiments were performed at laboratory scale, at pilot plant level in 1 to 10 tons column leaching experiments and at semiindustrial scale. In this last experiment a sector of the dump called Quebrada del Portezuelo, including 56.000 tonnes of low grade ore with 0.48% copper content, was leached during 585 days, recovering aproximately 23% of the copper (see Table 1).

TABLE 1. RESULTS OF A BACTERIAL LEACHING TEST AT THE CHUQUICAMATA DUMPS (5).

Ore	56,900 ton
Irrigation area	900 m2
Medium height	31 m
Initial grade	0.48 %
Chalcopyrite	27.2 %
Covelite	7.45 %
Pyrite	65.4 %
Leaching time	585 days
Acid consumption	8 Kgs/ton min.
Cu extraction	35 %
Cu recovery	23 %

The importance the role of the natural microflora in catalyzing the oxidation of pyrite to ferric sulfate and sulfuric acid and the oxidation of copper sulfides into soluble copper sulphate was evidenced in these experiments. The determinations of bacteria in the leaching solutions indicated 10^6 to 10^7 cells/ml, identifying the presence of Thiobacillus ferrooxidans, Leptospirilum ferrooxidans and some thermofilic bacteria. The semiindustrial operation served as a base to determine the parameters for designing and planning the industrial operation which is now at the stage of project development and is programmed to start in 1992 (7). The operation is planned to produce 40 tonnes of fine copper per day in an initial stage of development until 1996 and then production will increase to 80 ton per day. The dumps, with 35 to 40 m height average, including up to 2" lumps, will be irrigated with 1400 m3/hr of acidic solution on 400,000m2 irrigation area for each cycle of one year and a half. The feasibility of the project has been evaluated for 25% of copper recovery (7).

The treatment by vat leaching of the oxides from Chuquicamata mine since 1915 and from Mina Sur Mine (next to Chuquicamata mine) during the last 13 years, has resulted in the accumulation of 470 million ton of leached tailings with 0.3% average copper content. Metallurgical studies including leaching of the ore in pilot columns, heaps and in-place, in which 1000 m2 of the dump were irrigated, demonstrated the convenience of leaching the residues directly in the dumps. This alternative was supported by further geological information which indicated that the terrain where the residues are placed will garantee a high degree of solution recovery. The efficiency of the industrial process has been estimated at 65% of the total copper and the prospect is to recover 900,000 tonnes of fine copper in a 18 years period (8) Copper will be delivered as cathodes via solvent extraction and electrowining. In this process bacteria are assumed to play an important role in dissolving the residual sulfides, which are estimated to amount to 30% of the contained copper.

The present rate of production at El Teniente, the largest underground copper mine in the world, is 96,000 ton per day, produced by the block caving method. The subsidence effect has formed a crater of 2.7 Km2 total surface on the mountain slope, filled with broken low grade mixed ore. The reserves in the mine crater are estimated at about 390 million ton with 0.41% total Cu and 0.12% soluble copper (9). In 1985 a SX-EW plant started recovering the copper produced by the natural leaching of the ore bed and contained in the drainage water. Average production of natural leaching between October 85 and March 87 was 95 ton of copper per day. In-place leaching by controlled surface irrigation of the crater started in April 1987. Field tests in which 526 m2 of the crater were irrigated, helped in the determination of design parameters (see Table 2), which were

TABLE 2. DESIGN PARAMETERS FOR IN-PLACE LEACHING PROJECT AT EL TENIENTE (9).

Irrigation rate	10 l/hxm2
Acid consumption	4.5 Kg/Kg Cu
Average copper concentration	2.24 g Cu/l
Rest cycle	every other year
Solution recovery	90 %
Area productivity	0.1 t Cu/m2

used to demonstrate the feasibility of the operation. The facilities necessary to implement the project included 23,000 m2 of buried drippers, fresh water collection and a flow system capable of feeding from 20 to 110 l/s, sulfuric acid storage and pumping system and a solution dosification system before irrigation. Plant capacity of 25 Ton Cu/day is expected to be attained by the end of 1988, after ending the installation of the drippers. Considering the area productivity of 0.1 ton/yr m2, the production potential will increase from 12,000 tons Cu/yr in 1990 up to 38,000 ton Cu/yr in 2011, with the increase in the irrigatable area (9).

About 30 % of the 14,500 ton of copper produced annually by the Pudahuel Mining Society, corresponds to the bacterial leaching of non-chalcopyritic sulfides contained in their mixed ores. In 2-3 years all their copper production will be based on bacterial leaching as the secondary leaching will become predominant with the exhaustion of the oxides. The company claims to have available a technology ideal for controlling and optimizing the bacterial activity in their leaching heaps (10).

There are several additional sources in the country, with materials suitable to be treated by bacterial leaching. There is a large production of overburden and low grade ores in the exploitation of Los Bronces, owned by Exxon. The management estimates that 1.5 million ton of fine copper could be recovered from those materials by applying bacterial leaching, which will represent 10% of their total estimated production (5). Copper is present mainly as chalcopyrite. Additional 1.5 to 2.0 million ton of fine copper are expected to be recovered from the bacterial leaching of wastes and low grade ores produced after the exploitation of Quebrada Blanca and Pelambres mines (5). There are also inmense reserves of copper in the tailings from concentration plants, reserves which increase at a rate of about 200,000 ton of fine copper per year.

The sulfuric acid situation.

Sulfuric acid consumption represents an important share of bacterial leaching operating costs. Its availability and price are relevant factors to be taken into account when assesing the feasibility of any bioleaching operation. Most of the sulfuric acid in Chile is produced and consumed by the mining industry.

Sulfuric acid consumption is about 1700 tpd (1984) of which 94% is consumed by the mining industry. Currently only 14% of this acid is produced from sulfurous gases obtained at the smelting plants, being the rest based on sulfur as raw material, but in the future this situation will change. Increasing demands for improved atmosferic pollution control has increased the pressure for the installation of sulfuric acid plants which will utilize gases from the main copper smelteries.

Acid production from smelting gases will be increasingly attractive with respect to acid production from sulfur. The introduction of technological improvements such as the modified El Teniente converter and the replacement of combustion air by oxygen enriched air in some copper smelting plants, will produce more concentrated sulfurous gases which will result in the production of much cheaper acid. It is expected that in the future sulfuric acid plants using sulfur as raw material will operate only to cover the acid supply at times of peak demand or when the plants based on sulfurous gases are not operating. From the projection of the increase in copper concentrate production, the sulfuric acid potential output for the year 2000 will be 15,000 tpd, and will cost about US$40/ton(11). There are already concrete projects for sulfuric acid plants from smeltery gases at ENAMI's Ventanas (525 tpd), ENAMI's Paipote (240 tpd) and CODELCO's Chuquicamata (1,200 - 1,500 tpd).

The inherent limitations to stock large amounts of sulfuric acid creates a close link between the production of this reagent and its consumption and this is why the producers themselves have to encourage the consumption of their product. In practice the increase in acid production in Chile will be closely linked to the implementation of large bacterial leaching operations which will consume important amounts of it. Bacterial leaching projects will benefit from the availability of large supplies of low price sulfuric acid produced from sulfurous gases. At the same time they will contribute to the feasibility of these sulfuric acid plants.

RESEARCH AND DEVELOPMENT

A comprehensive programe of basic and applied research on bacterial leaching started in 1983 funded by the UN Development Programe (UNDP), the UN Industrial Development Organization (UNIDO) and government agencies. In a second three years stage started recently, CODELCO-CHILE participates as the main local funding office. The program combines the efforts of universities, applied research centers and industry towards the final aim of developing more efficient bacterial leaching processes and increasing their scope of application in the local mining industry.

In the basic research areas, teams at the Department of Biochemistry at the University of Chile and Department of Cell Biology at the Catholic university of Chile, are investigating the genetics, physiology and biochemistry of leaching bacteria. Applied research at the University of Chile's Department of Chemical Engineering and Mining Engineering and the Catholic University of Valparaiso's School of Biochemical Engineering, focuses on the fundamentals of chemical and biochemical engineering of bacterial leaching and the study of the metallurgical transformations ocurring in the process. Testing bacterial leacning processes in the laboratory, pilot plants and eventually on an industrial scale, is the responsibility of the Institute of Technological Research (INTEC-CHILE) and the Mineral and Metallurgical Research Center (CIMM), which also serve as link between the mining industry and the scientific groups. According to a recent evaluation by a UN team of independent experts, the three initial years of the programme have enabled the development of a local interdisciplinary group in bacterial leaching with an expertise "equal or better than the existing in the international community" (12).

Some notable results have been achieved in the project so far. To enable genetic manipulation of Thiobacillus ferrooxidans, a method of identifying different strains has been developed, producing a kit that will let field personnel with little training characterize different strains(13). Methods to introduce functional DNA into T. ferrooxidans by bacterial conjugation have showed promising results (14). The goals of this line are to develope optimized strains with increased microbial growth rate, improved resistance to heavy metals and to temperature changes.

Studies on the influence of organic agents on the activity of T. ferrooxidans (MACS), showed that solvent extraction reagent (e.g. Lix - 622, Lix - 864, ESCAID - 100) affect very little both the growth and copper sulfide dissolution ability of this strain, while both are marquedly reduced in the presence of flotation reagents (15). A Central bank of identified and characterized native microorganisms from different mine locations has been set up, and a program to select the ones with the highest resistence to mercury, molybdenum, arsenic, chlorides and temperature changes is underway.

The understanding and control of direct and indirect action during the bacterial leaching of sulfides is very critical for an efficient utilization of the catalytic action of T. ferrooxidans. Studies on the dissolution of pure chalcopyrite showed that the catalytic action of these bacteria mainly rests on its ability to keep a highly oxidative solution by producing ferric iron (16). Direct bacterial attack becomes more relevant when chalcopyrite is associated to species like pyrite, as in the case of concentrates (17), possibly due to the presence of galvanic interactions. However, as direct action depends on the access of the bacteria to the sulfide surface, its effect is reduced in the case of low grade ores, where the mineral particles are disseminated in a gangue matrix, far from the solution (18). In a related line, a bioelectrochemical reactor for the preparation of very dense cultures of bacteria has been developed, which should help in providing an independent control on the free and adhered bacterial population during leaching (19). Efficiency of direct bacterial action depends on the nature of the bacterial attachment to minerals and experiments in progress are leading to demonstrate the participation of the outer hypopolysaccharide in this mechanism (20).

The efficient design and manipulation of complex operations such as bacterial leaching can be better approached with the aid of mathematical models which provide a useful tool for rationalizing the interaction of the most important operating parameters. A mathematical model for the leaching of low grade ores was developed, considering the catalytic action of Thiobacillus ferrooxidans attached to the ore as well as in solution. The model was succesfully used in simulating the behaviour of bacterial leaching of low grade ores in pilot columns (21,22). The model is now being modified to extend its application to heap leaching operations and will be used in the future as a base for the design and control of this type of operation.

A 2,000 ton heap leaching test with a copper precipitation circuit, was designed, built, operated and monitored in Vallenar, a region located in the North of Chile (23). The heaps, made with ores from six different nearby locations, were intended to promote and introduce this kind of technology to small and medium sized copper producers in the region, and a manual of the operation was distributed (24). The operation also served to test some design and operational concepts at industrial scale, and to evaluate the feasibility of the process on materials of different characteristics. In the near future other semi-industrial and industrial bacterial leaching operations will be operated and controlled using the expertise developed under this R & D program.

CONCLUSIONS.

In the Chilean context, where the availability of cheap sulfuric acid is combined with a relatively good water supply in the mining region, bacterial leaching processes pose a concrete alternative for the economical recovery of large reserves of marginal copper ores.

The experience gained from the increasing number of local industrial bacterial leaching operations combined with the strong research effort on the basic and applied aspects of these processes, place Chile in a good position to play a leading role in the development and application of metallurgical routes based on this technology. Mastery of bioleaching technologies may not only allow Chile to stay ahead as the leading copper supplier, but also give its mining industry a head start in applying the technique to the recovery of other locally abundant metals such as gold, silver and uranium.

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REFERENCES

1.- Comisión Chilena.del Cobre and Servicio Nacional de Geologia y Mineria (1988).

2.- G.J. Olson, R.M. Kelly, "Microbiological metal transformations; biotechnological applications and potential", Biotech. Progress,2(1986) 1-15.

3.- L.E. Murr, "Theory and practice of copper sulfide leaching in dumps and in-situ", Min. Sci. Engng.,12(1980) 121-189

4.- A. C. Warhurst, "The application of biotechnology in developing countries. The case of mineral leaching with particular reference to the Andean Part Copper Project", UNIDO/IS-450 (1984).

5.- "Impact of bioengineering on the national development", Gerencia de Desarrollo, CORFO, AM86/40 (1986), Santiago, Chile.

6.- A. Pincheira, J. Heller, "Bacterial leaching of low grade copper ores", Revista Minerales, Vol. 41, N 41, p 13-20.

7.- J. Heller, CODELCO-Chile, División Chuquicamata, Personal Communication (1988).

8.- J. Perez F., "Leaching of leached tailings in dumps", in the 34th Conference of the Chilean Institute of Mining Engineers (1983).

9.- A. Ovalle, "In-place leaching of a block-caving mine", in Copper 87, Vol.3: Hydrometallurgy and Electrometallurgy of Copper (W.C. Copper, G.E.Lagos and G.Ugarte, eds.), Facultad de Ciencias Fisicas y Matemáticas, Universidad de Chile (1987), p.17.

10.- R. Montealegre, Sociedad Minera Pudahuel, Personal Communication (1988).

11.- R. Stefanowski, " Some considerations about sulfuric acid in Chile", in the 32nd Conference of the Chilean Institute of Mining Engineers (1981).

12.- "Why Chile leads the world in researching bacterial leaching of copper ores", UNIDO, Feature IDO/F/146 (1987).

13.- J.C. Jerez, Dept. of Biochemistry, U. of Chile. Personal Communication (1988).

14.- E. Hevia, G. Droguett, H. Sánchez, B. Cáceres, P. Lau, A. Venegas, "Preliminary studies for genetic transfer from E. coli and P. patida to Thiobacillus species", op. cit. (9), p.91.

15.- J.C. Gentina, R. Rivera, F. Acevedo, J. Retamal, G. Schaffeld, "Influence of organic agents on the kinetics of bacterial leaching of copper ores", op. cit. (9), p.107.

16.- E. Almendras, F. Arriagada, S. Bustos, L. Herrera, P. Ruiz, T. Vargas, J. Wiertz, R. Badilla, "Surface transformations and electrochemical responses of chalcopyrite in the bacterial leaching processes", in Biohydrometallurgy 87: Proc. Int. Symp., University of Warwick, U.K.(1987), (in press).

17.- E. Almendras, S. Bustos, P. Ruiz, J. Wiertz, R. Badilla, "Behaviour of copper sulfide minerals under bacterial leaching", op. cit. (9), p.119.

18.- J. Wiertz, T. Vargas, R. Espejo, L. Herrera, R. Badilla, "Bacterial leaching of low grade copper ores", in XI Inter-American Conference of Materials Technology (1987), Santiago, Chile.

19.- S. Bustos, R. Aguirre, H. Fuentes, R. Badilla, J. Allende, "A method for thr production of high concentration bacteria inoculum for use in bacterial leaching", Patent Application, Chile (1987).

20.- M. Rodriguez, B. Gómez-Silva, S. Campos, A. Ferreira, "Principal molecular components of the outer membrane of T. ferrooxidans. Mechanism of attachment of the organism to minerals", op. cit. (9), p.63.

21.- J.A. Castillo, M.N. Herrera, T. Vargas, R. Badilla, H.J. Neuburg, "Modeling of a bacterial leaching column for copper sulfide ores", op. cit. (9), p.149.

22.- J. Castillo, M. Herrera, L. Herrera, H. Neuburg, T. Vargas, J. Wiertz, R. Badilla, "Kinetic column leaching model for copper containing ores", op. cit. (16).

23.- "Bacterial leaching applied to small and medium-seized copper mining", Gerencia de Desarrollo, CORFO, AM86/40 (1986), Santiago, Chile.

24.- "Manual of bacterial leaching: small and medium-seized copper mining", Gerencia de Desarrollo, CORFO, AM86/57 (1986), Santiago, Chile.