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Bacterial Leaching: A Potential for Developing Countries

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Abstract

Although bacterial leaching or the recovery of metals from ores through the use of bacteria, is not a new technology, the optimization of the process is still in its development stages. Bacterial leaching occurs when certain bacteria which inhabit the relatively acidic waters of mines, interact with the ore to release an effluent from which the metal content can be recovered quite easily. The process has occurred in nature for hundreds of years. However, scientists have only recently started to examine means by which this process may be optimized, reducing thereby some of the highly capital intensive mining and extraction procedures in conventional mining.

Bacterial leaching offers many advantages over conventional technology. It is a natural process which already occurs in mine dumps, cutting out the costs of mining the ore and bringing it up to the surface. Furthermore, it has been discovered that bacteria can leach ores with a grading of as low as 0.01 percent, which increases substantially the amount of metal which can be recovered. Because the use of this technology can lead to the production of metal in a relatively pure form at the mine site, it bypasses the use of smelters, thereby reducing damage to the environment. This method is also advantageous to developing countries which often do not possess the capital to construct smelters and have to ship the ore overseas for refining, thereby losing the advantage of value added.

This study examines the use of bacterial leaching in the recovery of five metals, gold, silver, copper, cobalt and manganese and the potential this technology holds for developing countries. For this we also examine the economics of bacterial leaching in comparison with conventional processing techniques used in mining. The goal of the study is to demonstrate the viability of bacterial leaching as an alternative to conventional technologies especially to developing countries.

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*. The author is currently working at the International Federation of Institutes for Advanced Study (IFIAS) in Maastricht, the Netherlands as a Programme Officer in the Biotechnology Programme. A substantial amount of the research in this paper is based on earlier research conducted at IFIAS, which is soon to appear as part of the IFIAS Biopolicy Research series. I would like to express my thanks to Dr. Alyson Warburst from SPRU at the University of Sussex and IFIAS for their help in the research and writing of this report.

1. Introduction

Bacterial leaching, or the action of bacteria on mine ores to release an effluent containing metal is a natural process which has occurred for centuries. Bacteria which live in the relatively acidic waters of a mine are able to dissolve normally insoluble sulphide ores to release various metals in an effluent form from which the metal can then be recovered relatively easily. Similarly, scientists have recently discovered that bacterial leaching can be used for refractory gold, the extraction of which is not normally possible. Refractory gold is freed from the ore through bacterial leaching and the metal can then be recovered through normal leaching procedures. Bacterial leaching can be applied for the recovery of other metals as well in this way.

Although the technology is relatively old and would occur naturally regardless of human involvement, recent research in this field has developed quite rapidly. Present research can be distinguished from past applications because it focuses on the *optimization* process. This includes the use of genetically engineered bacteria to accelerate leaching or altering pH levels in the mining environment to improve recovery rates.

The development potential for bacterial leaching in mining throughout the world is enormous. Lower and less sophisticated capital requirements as well as an increase in the recovery of metal from ore offer bright prospects for the future.

Recent years have also seen an acceleration in the applications of bacterial leaching. The impetus for this change has been provided by a number of new developments which occurred over the last decade. Mining companies have had to cut costs and adhere to stricter environmental regulations in developed countries. The collapse of most base metal prices in the late 1970's and early 1980's also resulted in a worldwide restructuring programme as mining companies were forced to lower costs of production and this period witnessed large mine closures in many developed countries. The development of advanced material technology has provided a considerable threat to conventional metals as well. These are some of the more important changes which have forced the usually conventional mining industry to consider bacterial leaching as a viable option, resulting in a substantial increase in research and applications of biotechnology in the mining industry.

For the developing countries, the possibilities for using bacterial leaching are excellent. In the past, less sophisticated mining technology in these countries has resulted in higher grade ores being rejected. Thus the dumps of "waste" which have been created at mining sites contain ore of a much higher grade than presently being mined in these countries. Biotechnology can be used to recover metal from these dumps without the extra costs of mining the ore, enabling these countries to develop their mineral resources more thoroughly.

This document examines bacterial leaching with respect to five metals: gold, silver, copper, manganese and cobalt. Current research includes examining the process by which bacteria act to liberate metal from the ores as well as the actual application of this technology on mine sites. However, before a technology is considered viable, its economic feasibility in relation to conventional technologies has to be examined. Hence we will look at the economics of bacterial leaching and present the results of a previous study carried out for copper and gold as well.

The paper intends to show the advantages of bacterial leaching over other technologies presently used by the mining industries, not only economically, but also in terms of environmental protection. Moreover, developing countries have an especially large role to play in this respect not only because bacterial leaching reduces the need for expensive capital investments but also because it enables extraction from dumps which already exist at mine sites and were previously considered uneconomic to process using conventional technologies.

2. Bacterial Leaching

Bacterial leaching, although we are only now becoming familiar with it, has occurred in nature for hundreds of years. In fact the earliest recorded case of bacterial leaching at a mine site was in Rio Tinto in Spain some 300 years ago.[1] The bacteria which thrive in the somewhat acidic waters of mines function as oxidizing agents and obtain energy for growth through the oxidation of iron and sulphur. These microbes require the fulfilment of certain conditions to ensure their survival which in turn facilitates bacterial leaching. These conditions include ample amounts of oxygen, a highly acidic pH and specific nutrients.[2] While the process is ancient, scientists have begun examining the process only very recently. In fact research on applications of bacterial leaching to copper and uranium recovery led to a Kennecott Copper Corporation patent only as late as 1958.[3]

Today, this process is being studied more closely by the scientific community and interest in mining companies has also increased due to lower prices during the late 1970's and early 1980's. The discovery of bacteria which are known to oxidise ores other than sulphides has led to research on the recovery of metals other than copper and uranium. Leaching techniques have also become more advanced due to the close relationship between the degree of optimisation and recovery levels. We can now identify three specific methods of bacterial leaching at mine sites:

<u>Dump Leaching</u>

At present, much of the ore which is retrieved to the surface from mines and is considered to be waste material is left lying in dumps. Sulphide ores can be leached from these waste dumps by spraying a slightly acidic solution containing bacteria. The solution percolates through the dump, dissolving sulphides in the process, to produce an effluent. The metal can be recovered from the effluent when the mineral concentrations of the solution are high enough (around 2g/litre), by precipitation on scrap iron or through more efficient solvent extraction and electrowinning techniques.

The rate of metal recovery is probably the lowest for this kind of leaching (usually less than 40 percent of total metal content recovered), because of the lack of optimization. The dumps used for bacterial leaching are not specially constructed for this method of mineral recovery. For efficient recovery, not only do the bacteria have to be kept in optimized conditions, but so does the ore. In the case of dump leaching, the solution is unable to reach the centre of the dump and therefore unable to efficiently leach the entire ore heap. However, as a result of this, the costs associated with dump leaching are generally low with additional costs imposed by the introduction of new equipment such as acid resistant pipes, pumps and collecting tanks. The total costs associated with dump leaching usually range from between US$ 1 million and US$ 2.5 million depending upon factors such as dump dimensions and topography. Operating costs are minimal, an efficient process resulting in self generation of acid and no additional purchase of energy.[4]

Heap Leaching

As its name suggests, this process involves the leaching of marginal ores during on-going operations and of overburden from newly developed open pit mines, in heaps designed to be constructed and operated according to parameters for optimal bacterial activity at the mine sites. Initial capital and operating costs are therefore higher than they are for dump leaching but as a result the recovery of metal is considerably higher, ranging from between 40 percent and 80 percent depending upon the extent of optimization.

Initial costs are normally associated with the designing and optimization of heaps which facilitate efficient aeration and temperature control as well as extensive testing to maximize metal recovery. Higher capital costs are also required for blasting and crushing of ore the extent of which depends upon the natural particle size of the ore. Investment costs for heap leaching have been estimated at between US$ 5 million and US$ 50 million.[5]

Concentrate Leaching

Also known as vat leaching, this method of bacterial leaching is the most capital and skill oriented. Leaching of ores takes place in confined and optimised environments, allowing more control over the process. This method in the future has the potential to provide an alternative to environmentally damaging processes such as smelting and roasting. As yet however, not enough is known about the microbiology and genetic make-up of the bacteria involved and the development of this method is still in its early stages with a few companies such as Giant Bay Resources Inc. and Coastech Research Inc. carrying out experiments in confined environments where tight controls can be maintained.[6]

3. Biotechnology Applications in Mining

3.1 Gold and Silver

Much of the world's current research in bacterial leaching has concentrated on gold. The precious metal has seen a fairly explosive price rise in the last decade or so. The reason we include silver in the analysis together with gold is that the two metals are almost always found together in nature. It is therefore difficult to study bacterial leaching of silver without mentioning gold and vice versa.

Bioleaching of gold especially certain types of mineralisation is now being commercialised by both biotechnology firms as well as by mining companies all over the world. Gold occurs in rocks either in nugget form or as an inclusion into sulphide minerals such as pyrite, arsenopyrite, pyrrhotite, galenite, sphalerite and silicate minerals. Bacterial leaching as well as other forms of processing have proved popular with gold which has seen its price rise almost continuously since the abandonment of the gold standard system in the 1970's. However, it is in the area of refractory gold that bacterial leaching has shown its true potential.

The reasons for refractoriness in gold may be many: inclusions of submicron gold in sulphide minerals, especially pyrite and arsenopyrite; the presence of iron, copper or lead minerals which consume cyanide by forming metal-cyanide complex ions are some.[7] These refractory ores do not react to conventional cyanidation procedures. Instead, it has been suggested that pretreatment with bacterial solution makes it possible to recover gold through cyanidation or cyanidation-CIL. Successful applications of bacterial leaching to refractory gold have been demonstrated a number of times both through laboratory testing as well as applications.[8]

Most of the work in this area has concentrated on the use of the mesophilic bacteria *T. ferrooxidans* which obtains energy from the oxidation of ferrous iron and reduced sulphur compounds. Refractory gold bearing sulphide minerals such as arsenopyrite and pyrite can therefore be oxidised by *T. ferrooxidans* to recover gold.[9] However, Coastech Research in Canada has begun investigating alternative bacteria which may be better applied to the leaching process. One of these which was isolated in 1972 and is receiving considerable attention is *Sulfolobus acidocaldarius.*

In a study published in 1986, researchers from the University of Warwick have tested and discussed the advantages of this bacterium.[10] Sulfolobus-like bacteria were obtained via pyrite enrichment cultures of Icelandic hot spring and English coal pile samples. Chalcopyrite, pentlandite, pyrite and nickel-containing pyrrhotite concentrates were degraded during the autotrophic growth of iron and sulphur oxidising strains of the bacterium at temperatures of 70 degrees celsius. Preliminary results were encouraging for *sulfolobus* showing that while *T. ferrooxidans* initially produced better oxidation kinetics, oxidation rates for *sulfolobus* increased with increasing pulp density up to the highest density.

More recent work studying the leaching of arsenopyrite using *sulfolobus* at high temperatures at the University of Umea reveals that the bacteria produced stable levels of metal dissolution and promising leaching rates at temperatures of as high as 70 degrees celsius.[11]

Another thermophilic bacteria, *Sulfolobus brierleyi* was also tested, this time on pyrite leaching.[12] Results showed that the total amount of iron released by *T. ferrooxidans* at 37 degrees celsius was considerably lower than the amount of iron released using *S. brierleyi* at higher temperatures of 60 and 68 degrees celsius. Similarly, Norris and Barr[13] from the University of Warwick confirmed the ability of thermophilic bacteria such as *Sulfolobus* to leach pyrite at high temperatures. However, bacterial activity is reduced when mineral concentrations are increased. For this reason, further research needs to be carried out on the screening and study of different thermophilic strains with respect to their tolerance of high solid concentrations as well as improvement in the design of reactors.

Because of the importance of gold as a metal as well as the occurrence of silver together with gold, bacterial leaching research has not concentrated much specifically on silver recovery. This was partly due also to the fact that previous tests of microbial leaching of silver proved to be unsuccessful.[14] According to Ehrlich[15], a probable reason for this lack of success of leaching of silver containing sulphide ores is that silver ion is perceived to be very toxic to microorganisms in general, discouraging their use in bioleaching of silver ores. Ehrlich however obtained significant results in his test studying the leaching of silver from a mixed sulphide, silver containing ore.

Two samples of ore from the same orebody in Idaho were used, one for a batch leaching experiment and the other for continuous leaching. The culture used in the experiments was a strain of *Thiobacillus ferrooxidans.* In the case of the batch leach tests, pairs of Erlenmeyer flasks were used, one inoculated with a solution containing *T. ferrooxidans.* Similarly, for the continuous tests, two reactors were used, one inoculated and the other uninoculated. Three different media containing different levels of iron were introduced. The results of the batch leaching show that of the three media, 9K Fe medium was by far the most effective, *T. ferrooxidans* accelerating the leaching of Ag, Cu and Zn in 9K and

0.9K Fe medium but in 0K medium its effect was slight for Cu and Zn and absent for Ag.

In the case of continuous leaching the overall rates of silver recovery in the reactor containing *T. ferrooxidans* were satisfactory (77.5%). Moreover, leaching rates in the continuous process appear to have been relatively selective for silver, the final results showing relatively smaller levels of other metals including copper, zinc and lead recovered in the inoculated continuous test reactor as compared to the inoculated batch test results. This selectiveness may have some practical implications: firstly, depending upon the recovery process, it would facilitate the recovery of silver from the pregnant solution by lessening interference from Cu and Zn, and it helps to preserve much of the Cu and Zn in the ore for subsequent extraction by batch leaching or other suitable processes.

Another series of experiments carried out recently shows that the use of T. ferrooxidans to treat refractory gold-arsenic concentrates by tank leaching is much more profitable than alternatives such as cyanidation and autoclave leaching. Moreover, bacterial leaching is environmentally safe when compared to conventional processes such as pyrometallurgical processing.[16] The rate of recovery in the controlled laboratory conditions was as high as over 90% for gold and 80% for silver from the concentrates. Processing in a closed system also reduced the danger of environmental pollution from the substances released during leaching.

Commercial applications of this form of recovery have increased considerably in the last five years or so. In Canada bioleaching plants have been run successfully by Giant Bay Resources Inc. The effectiveness of this process has been demonstrated by a number of pilot scale tests. Bench scale tests initially tested approximately thirty different concentrate samples from sites in North America and Australia to determine their response to biooxidation. Of these samples, three were used in continuous bench scale analysis. Finally, a mixed pyrite-arsenopyrite concentrate from Eastern Canada was used in a pilot plant operation which lasted from August to December 1985.

The results during the three stages of operation showed cumulative sulphide oxidations of 62 percent after stage one, 78 percent after stage two and 94 percent after stage three. Some of the advantages offered by bacterial leaching: operation at room temperature and pressure; efficient use of oxygen from air as the oxidant; and disposal of iron, arsenic and sulphur as environmentally safe products.[17] Since then, Giant Bay has been involved in a number of commercial applications, most of them joint ventures using biotechnology on a trial basis. Most of these ventures have involved sulphide gold deposits in Australia and Canada. The world's first gold dore bar was recovered from the treatment of refractory gold ore by bioleaching in September 1987 [18] at the Salmita gold mine in the Northwest Territories in Canada.

In the case of Equity Silver Mines Ltd's open pit in British Columbia, the company conducted a feasibility analysis for bacterial pretreatment of the ore by constructing both laboratory and pilot scale bioleaching test facilities.[19] Preliminary laboratory testing of the ore was carried out at BC Research's laboratories. Batch testing revealed that gold recovery by cyanidation appeared insensitive to the degree of pyrite oxidation. However, silver as confirmed by earlier studies, appears highly dependent on Fe extraction. Thus, depending upon parameters such as the price of silver, the tests indicated that it may be advantageous to minimise the degree of oxidation at the expense of silver recovery, to minimise treatment costs of byproduct bioleachate constituents.

The pilot plant was set up mainly using the same parameters as for the batch tests. The results show that although a combined Fe + As extraction of 80-90% is not justified for additional gold recovery which appears to remain constant after about 80% extraction, silver recovery continues to improve as sulphide oxidation continues. The final result at Equity was the setting up of a 2 tonne per day pilot scale trial where the bioleach circuit sizing and operating parameters were maintained at 80-90% combined Fe + As oxidation as silver prices were not high enough to warrant the additional capital and operating costs associated with increased silver recovery.

Newmont Gold has recognised the importance of bacterial leaching for recovery of refractory gold such as found in the orebodies of the Carlin Trend. Ongoing research on the use of the microbe *Thiobacillus ferrooxidans* and other similar bacteria has resulted in the setting up of a series of pilot facilities for bioleaching.[20]

Although most of the commercial applications discussed thus far have concentrated on developed countries, bioleaching of refractory gold and silver has a great potential for developing countries as well. One of these countries where research in bacterial leaching for refractory ores seems to be relatively advanced is Zimbabwe. Zimbabwe has a number of refractory gold and silver deposits and interest in bacterial leaching has led to considerable research in this field. The Institute of Mining Research at the University of Zimbabwe has examined the potential use of biotechnology in two recent reports.[21]

In laboratory testing, a dynamic system was designed for gold concentrates. The first experiment was performed at a 5 percent pulp density on an arsenopyrite concentrate from the Vabachikwe mine containing 5.5 g Au/tonne after cyanidation. The recovery of gold after bacterial leaching increased from 4 percent to 75 percent. From these results it was proposed that a continuous leaching process be designed and tested to confirm these results.

In a second experiment, refractory gold concentrate consisting mainly of arsenopyrite was tested from the Bar 20 mine, Gwanda. The results of this experiment showed a 67% oxidation of sulphides in fifteen days and an improvement in gold recovery from 36 percent to 86 percent. This was followed up by a final experiment at Broomstock Concentrate Kwekwe. Here, the global oxidation of sulphides was around 55 percent and gold recovery increased from 25 percent to 78 percent. The promising results obtained from these experiments have led to the conviction that while further work is needed to enlarge the scale of bacterial leaching, bio-oxidation has an important potential in the treatment of refractory gold ore in the context of Zimbabwe.

Similarly, the epithermal deposits of the Pacific rim contain refractory ore for which bacterial leaching has potential. The recently developed Porgera mine in Papua New Guinea contains ore which is refractory in nature. Depending on the circumstances particular to this mine, bacterial leaching if viewed as an alternative to pressure oxidation as a form of pretreatment before cyanidation, might prove to be cheaper and more effective. The gold project still in its evaluation stages on Lihir island once again has refractory ore which needs to be pretreated before the gold can be extracted. In feasibility analyses bacterial leaching should indeed be examined along with all the other alternatives. However, this remains to be seen since mining companies tend to be conservative in the adoption of new technologies. In fact, in a recent survey of copper and gold deposits in Papua New Guinea, bacterial leaching does not even get a mention as a possible alternative to other pre treatment methods for refractory ore.[22]

3.2. Copper

Being one of the most important base metals, copper is especially important to developing countries since some of the largest producers of copper in the world are developing countries. In addition copper is especially interesting in relation to this study because of the enormous progress made in bacterial leaching especially by developing countries. Copper is contained mainly in sulphide ores. Unlike gold, most of the bacterial leaching research for sulphides concentrates on dump and heap leaching which required less sophisticated technology and have lower capital and operating costs than concentrate leaching which is used for gold. Because of this, laboratory testing as well as commercial applications of sulphide leaching are becoming more and more common in developing countries as well.

More recently research has developed to the stage of examining continuous leaching systems which would be more desirable for industrial applications. One such study of bacterial leaching of copper sulphide ores[23] shows that *T. ferrooxidans* provides high copper extraction rates in all batches tested except for those containing Chalcopyrite. This may be due to the formation of iron precipitates on the surface of the chalcopyrite particles, inhibiting the growth of bacteria. Nevertheless, the high recovery rates of 65-84 percent show that bacterial leaching is a viable alternative to conventional technology.

North America, especially Canada, has been at the forefront of research on bacterial leaching of sulphide ores. Canadian Universities supported by the mining industry have carried out a considerable amount of research on the various advantages and difficulties posed by different bacteria in biotechnology. The Flin Flon mine in Manitoba has been the subject of two separate studies.[24] Both studies used sulphide ores from the Flin Flon mine to carry out shake flask experiments using *T. ferrooxidans* and *T. thiooxidans* in different cultures. Both have concluded that the highest rates of metal recovery are seen when *T. ferrooxidans* and *T. thiooxidans* are combined in the leach solution.

A recent project at the Flin Flon mine was initiated by the Hudson Bay Mining and Smelting Company.[25] The results again show the most efficient recovery of metal using mixed cultures of *T. ferrooxidans* and *T. thiooxidans*. Hudson Bay Mining and Smelting is currently using the data obtained from shake flask and column tests to determine the cost of leaching the experimental block of mined-out and backfilled stopes at the mine. If these experiments appeared to be economically feasible, the company was expecting to set up a pilot leaching plant.

Experiments with biotechnology have recently been carried out in South-west Spain.[26] The ores of the region, which contain substantial amounts of copper, lead, zinc, silver and gold are currently crushed and concentrated by differential flotation. Because of the pyrite content, another alternative is to produce bulk concentrates which can then be treated by a hydro or pyrometallurgical process. Bacterial leaching is considered to be a cheaper and more efficient alternative to these processes. The experiments using *T. ferrooxidans* show that leaching in the presence of bacteria was faster and more effective than in their absence. Similar leaching experiments using *T. ferrooxidans* and *T. thiooxidans* have been carried out in Finland.[27]

The relatively low prices of copper in the last decade have prompted more research into in-place or in-situ bacterial leaching. It has also been encouraged by the US Bureau of Mines as well as the Canadian Department of Energy, Mines and Resources (CANMET), the latter contracting the mining company Noranda to carry out a pre-feasibility study of in-situ leaching of copper.[28] One of the mines owned by Noranda is already involved in bacterial leaching. Lakeshore mine in Arizona, USA which in 1983 changed from block cave mining-vat leaching of its oxide deposit to a bore-hole in-place leaching of low grade ore, is currently recovering approximately 700 tonnes per month of copper from solutions assaying about 1.7 g/L copper.

The mine chosen by Noranda for study was the Geco Mine in Ontario, Canada. Unfortunately the results were not encouraging for bacterial leaching whose cost varies from mine to mine because of different mining environments.

Recently, an in-situ pilot plant was set up at the San Valentino di Predoi mine in Northern Italy.[29] Initially, shake flask tests were carried out using *T. ferrooxidans* strains isolated from mine waters. The results confirmed a high leaching rate and accordingly, a suitable bioleaching flowsheet was devised which has since been implemented.

In South Africa, large-scale bacterial tests were carried out in-situ at the Prieska Copper-Zinc mine.[30] In laboratory tests, leaching of zinc was far better than copper from Chalcopyrite. Despite the poor results obtained for copper, zinc recovery was high enough to encourage continued large-scale laboratory tests. However, here too, as in Canada, it was decided that in-situ bacterial leaching would not be a feasible alternative because of problems of adequate access for distribution of the lixiviant and the dimensions and attitude of the orebody.

In the developing world too, work on bacterial leaching of sulphides is continuing. The Andean Pact countries are possibly the leaders in the use of this technology in the Third World. As has been noted before,[31] several bacterial leaching industrial scale operations already exist in developing countries: a dump leaching operation at Bougainville in Papua New Guinea, a combined dump and underground leaching operation at Cerro de Pasco in Peru and a semi-optimised heap leaching operation at Cananea in Mexico. In addition, Centromin of Peru has designed a semi-industrial scale bacterial heap leaching plant to extract copper from low grade ore from overburden at Toromocho.

More recently, Mineroperu has submitted a proposal for bacterial leaching of copper for approval. The proposed process to be developed at Mineroperu's Cerro Verde unit will entail treating secondary sulphides by acid-ferric bacterial leaching to produce 15,000 tonnes per year of copper cathodes using existing facilities and floating the fines to produce 57,000 tonnes per year of copper cathodes.[32]

In Chile, laboratory as well as semi-industrial scale tests were conducted to help determine some of the parameters of an optimal bacterial leaching industrial project.[33] A mixed kinetic model describing the dissolution of low grade copper ores from the El Teniente mine in Chile was recently set up. Predictions from the model when compared with experimental data from a bacterial leaching operation in a pilot column showed surprisingly similar results.[34] Codelco in Chile has been using bacteria for dump leaching projects: one for treating low grade sulphides (0.2 to 0.5 percent) and the other for treating coarse middlings from its concentrator.[35]

In Panama, percolation leach testing has been carried out on ores from the Cerro Colorado copper deposit.[36] The recoveries were poor, jarosite deposition favoured by poor liquor distribution over and in the fairly alkaline rocks was probably a major cause of the cessation of leaching. In contrast, a major success was reported with bacterial leaching of Chalcopyrite concentrates from Mosaboni in India.[37] The tests were carried out first in shake flasks and then in a glass bioreactor using *T. ferrooxidans MCM B-231*. The experiments were largely successful, the bioreactor recovery rate reaching 88.64 percent, significantly higher than recovery rates of 70.24 percent in shake flasks. This significant improvement appears to be due to efficient aeration and consequent high rates of oxygen and carbon dioxide mass transfer achieved.

3.3. Manganese

So far, research on bacterial leaching has only concentrated on the group thiobacillus.[38] Thiobacilli are effective only when applied to sulphide ores. Much of the world's mineral wealth however, is contained in other accumulations. Manganese for example, can be found in the form of oxides, carbonates and silicates. There are however limits to the use of chemolithotrophic thiobacilli for these ores. This is because the energy supplying substrates (sulphides, iron (II), sulphate and sulphur) are missing and must be added to the ore. Moreover, the pH values (usually greater than 5) in the leaching solution have an inhibiting effect on the bacteria.

Several methods for leaching of manganese ores have been identified thus far. A feasibility test was carried out by the US Bureau of Mines for leaching of manganese from low grade oxide and carbonate ores. The presence of organic material including leaves and yeast resulted in an average leach rate of about 97% after 60 days.[39] This led them to conclude that microorganisms can be used to leach manganese from oxides and carbonates.

Another method of manganese leaching replaces the sulphur content, which in turn enables leaching by sulphide oxidising bacteria. The method which was patented in Japan, leaches manganese from an aqueous solution of manganese sulphate using bacteria to oxidise sulphur to sulphuric acid. Initially, the bacterium T. ferrooxidans was used to produce sulphuric acid. This proved unhelpful since manganese dioxide is almost insoluble in sulphuric acid. However, in the presence of T. thiooxidans, almost all of the manganese dioxide was converted into manganese sulphate at an extremely rapid rate.[40]

The use of heterotrophic bacteria also aids in the process of manganese leaching. In India, an ore containing 44% manganese was leached using cultures of *Pseudomonas sp.* and *Basillus sp.* Precipitation of the solubilized manganese was carried out with the addition of lime resulting in a 90% recovery rate after 90 days.[41] In the USSR, manganese was recovered using heterotrophic bacteria on liquid wastes. Once again the recovery rate was high, 90-96% in only 12 days.[42] An important conclusion here is that contrary to conventional beliefs bacterial leaching under certain circumstances may result in high rates of metal recovery in a relatively short period of time.

3.4. Cobalt

Cobalt is used mainly for the production of superalloys for use by the aerospace and other industries. In 1988, the two largest producers of cobalt, Zaire and Zambia together accounted for over 70% of total market economy production.[43]

Cobalt very often occurs in nature along with other sulphides, predominantly copper and nickel sulphides. Until now more emphasis appears to be placed on the biological recovery of these other metals. The fact that most of the world's cobalt is produced in these two African nations may partly account for the slow growth of bacterial leaching of cobalt. Indeed as we saw, the main reason why gold has received so much attention is linked to its price as well as the fact that a large amount of gold is produced in developed countries where more advanced technology and environmental legislation has provided incentive for mining companies to branch out into other methods of processing which are potentially cheaper and less harmful to the environment.

Some have also argued that because cobalt is largely produced in areas of the world which are potentially unstable, it is increasingly being regarded as a strategic mineral.[44] Interest in alternative means of producing cobalt is therefore likely to grow in the near future.

Some progress is already being made in this field. In South Africa, nickel and cobalt can usually be found together. However, although nickel deposits do exist in the country, they are usually low grade and disseminated in nature and with the present economies and technology, their exploitation is considered to be uneconomical.[45] Nickel in South Africa is principally found in pentlandite which contains quantities of cobalt. Conventional extraction techniques have so far been unsuccessful in extracting a high percentage of metal from this kind of ore in which mineralisation occurs as exsolved fine lamellae in pyrrhotite. The result is a dilemma as to whether grade should be sacrificed in favour of recovery. The South African Council for Mineral Technology (MINTEK) has therefore initiated a study examining other non-conventional means for extracting nickel from such ores. The study examined the agitated bacterial leaching of nickel sulphide, producing cobalt and copper as by products.

The semicontinuous process, showed a large increase in extraction rates for both cobalt and nickel after about 5 weeks, the leaching rate steadying to over 85% and 90% respectively after about 11 weeks of leaching. The authors of this study also designed a flowsheet which would justify bacterial leaching of nickel and cobalt on a practical scale. Although the economics of bacterial leaching for this particular case were not discussed, the authors argued that opinion in the mining industry is continually being adjusted to favour bacterial leaching as we see economic leaching rates which are competitive with more expensive and environmentally detrimental conventional processes.

4. Biosorption: The Environmental Benefits

A relatively new area of research in the field of bioleaching is biosorption, the process by which microbial biomass, living or dead aids in the removal of metals or toxic substances from waste material and industrial effluents. Research in this area ranges from the recovery of precious metals such as gold,[46] the recovery of cobalt,[47] copper binding,[48] to the accumulation of heavy metals and radionuclides by non-growing fungal biomass.[49]

At the Homestake gold mine in South Dakota, a process has been developed for the biodegradation of cyanide waste which removes free cyanide and metal complexes from effluent before discharge to the local watercourse.[50] The biomass that is recovered from bioreactors shows the presence of about 45 grammes per tonne gold. The fact that the presence of gold was not detectable in the feed to biodegradation indicates the extent of the scavenging power of the microorganisms.

The adsorption properties of a bacterium (*Bacillus subtilis*), a fungus (*Aspergillas aiger*) and two species of algae (*Chlorella vulgaris* and *Spirulina platentis*) were compared. All three are known to adsorb heavy metals. Results showed that the adsorption of gold tended to a maximum in the range pH 3-4 for all four organisms, with *Chlorella* showing the best results for pure gold chloride (90 percent adsorption in four minutes at 2 percent loading). For a potential industrial process, a semi-continuous process of selective gold recovery from dilute solution was also demonstrated using a column of alginate gel immobilized algae which although restricting the adsorption rate, enabled a high recovery of gold with good selectivity.

A similar comparative study looked at the role played by two bacterial strains and a unicellular alga in the adsorption of uranium, silver and gold, from barren solutions, small-scale in situ leachates and waste streams from metal finishing operations.[51]

Apart from their adsorption abilities, these microorganisms are also important in environmental conservation. Recent EEC directives against the discharge of industrial effluents including air pollutants such as sulphur dioxide produced by smelters as well as environmental legislation in the US and Canada has led to the increasing use of bacteria such as T. ferrooxidans in the mining industry. More recently the importance of harmless algae and fungi which can be manipulated into effective forms for metal recovery from mining operations and industrial effluent has been acknowledged.[52]

One such application is the AMT-BIOCLAIM process which applies biosorption for metals removal from wastewater.[53] The process which uses a granulated non-living biomass product for a metal removal agent (MRA) was tested on wastewater from a jewellery manufacturer and a manufacturer of precious metal compounds. Both kinds of gold cyanide wastewaters contained either very low levels of free cyanide (as in the case of the jewellery manufacturer's wastewater) or none at all (metal company's wastewater). Despite varying the volume of the sample and the pH level, the level of metal recovery especially that of gold was extremely good for both kinds of wastewaters.

Following up on this, a pilot plant for the removal of lead from an industrial effluent was set up by the owners of this process, Advanced Mineral Technologies Inc. and was run for 39 days. A stable and efficient removal of lead (98-99%) was achieved. The variation in pH did not influence lead removal, nor did the variation of lead content in the effluent which ranged from 0.01 to 4.30 mg/l.[54]

Thus the research which has been carried out in this new area of bacterial activity in the field of metallurgy shows that biosorption has both financial and environmental potential. However, it must be made clear that the field is extremely new, and the processes involved complex. Nevertheless biosorption has a substantial contribution to make both in terms of increasing annual metal production levels as well as providing incentives to companies which are at present required to treat wastewaters as part of the general effort especially in developed countries to clean up the environment.

5. Economics of Bacterial Leaching

Thus far we have shown that the use of bacterial leaching can be beneficial in terms of high recovery rates as well as the important side effect of reduced environmental pollution. However, before bacterial leaching can be convincingly portrayed as a feasible alternative to conventional processing technologies we have to examine the economic costs and benefits of the technology especially in comparison with some of the older techniques. This section is divided into two parts. The first will present a brief survey on the latest developments in the economics of bacterial leaching. Then we will present the results of an economic feasibility study[55] which considered orebodies of different sizes and ore grades as well as different forms of bacterial leaching in relation to copper and gold deposits.

5.1. Is Bacterial Leaching Economically Viable?

The work in this field initially began with refractory gold and silver since metal is rather difficult to extract economically from this kind of mineralisation using conventional cyanidation processes. Bacterial leaching seemed to be the only alternative and if it could be proved economical, would provide a feasible alternative for extraction of gold from refractory ores.

Preliminary experiments at Giant Bay Inc. with bacterial leaching for refractory gold-silver concentrates[56] led to an engineering feasibility study by Wright Engineers Ltd. The site chosen was in Northern Ontario and the results from this study would apply only to that site. Capital and operating cost estimates for the BIOTANKLEACH process were prepared at operating rates of 50, 100 and 200 tonnes per day. These were compared to capital and operating costs estimated for roasting and pressure oxidation at a rate of 100 tonnes per day. The results showed that the overall cost of the Giant Bay technique was significantly less than the two alternative technologies.

Similarly, researchers from Davy Mckee and University College Cardiff[57] compared bacterial leaching of gold from two pilot plants each with a different average grade and capacity with a pilot plant to treat a flotation concentrate without bacterial leaching. The results showed a definite advantage for bacterial leaching prior to cyanidation. However, the results also indicated that bacterial leaching could be most economically viable when the average grade of gold in the concentrate was relatively high (in this case the plant which appeared most economic contained 1.2 g Au/tonne assay). This is similar to the conclusion reached by our study on the economic viability of bioleaching of refractory gold.[58]

A number of others have recently also examined the feasibility of bacterial leaching in comparison with other technologies, both for gold[59] as well as for copper.[60] The copper study by BC Research first demonstrated a system of bioleaching of chalcopyrite. While the technical feasibility of bacterial leaching was established by the study, the economic analysis showed that bioleaching was only marginally competitive with conventional processes. However the authors argued that this may change if environmental restrictions forced higher smelting charges. Since the study was completed, environmental restrictions have become considerably more stringent and bacterial leaching may now be considered more competitive.

5.2. Bacterial Leaching of Copper and Gold Ores

Before concluding this study, we would like to present the results of a preliminary computer modelling exercise in which we attempted to determine the range of orebody sizes as well as methods by which bacterial leaching would be a feasible alternative to conventional technology.[61] As an example we used two kinds of orebodies, porphyry copper and refractory gold deposits. However, the model can be changed so as to carry out a similar analysis for other kinds of deposits, including the other metals presented in this study.

5.2.1. Description of Models and Methodology

The cost and revenue models were developed at the Royal School of Mines in London. They were constructed within the MECON system and incorporate models for capital and operating costs, revenue and tax regime. The currency used throughout the study was US dollars. The mineral exploitation models incorporated a data base of cost models which could be selected for the flowsheet cost centres which in turn were based on the unit operations. The various parameters of the flowsheet model can be simply modified to tailor the system to the flowsheet.

Cost Models: The cost models are based on a number of sources.[62] In these models the capital and operating costs are expressed mathematically in terms of capacity, that is,

$$\text{COST} = \text{A X CAPACITY}^{\text{B}}$$

where A and B are constants. A is the magnitude factor and B is the scaling factor.

The US Bureau of Mines claims a reliability for their cost models of plus or minus 25%. The MECON system has been able to achieve plus or minus 30%.

These valuations are of course highly dependent on technical consistency and accuracy where accuracy is dependent on the input.
Revenue Models: Revenue was calculated by applying metal prices to the recovered metal. These required the estimation of in situ mined grade, dilution, recovery, production rate and metal price. We used a geostatistical model to produce the relationship of average grade above the cut-off grade to the proportion of reserves above the cut off grade. The model used a log-normal distribution with a constant coefficient of variation. In this study, the values used for the coefficient of variation were 0.22 for copper and 0.52 for gold. For simplicity and because of time constraints, we assumed that the copper ore bodies contained only copper and the gold ore bodies only gold.

Taxation: A "typical" tax regime was chosen: a 40 percent tax rate, a 5 percent royalty rate and straight line depreciation over 10 years for capital allowance costs. Mining policies such as tax systems and royalty rates play an important role in the economic feasibility of a mining project.

Methodology: The value of the ore body under consideration was measured in terms of the Net Present Value discounted at 10 percent. Note that the NPV (10%) increases as cutoff grade increases to a maximum, and then falls. The value of an orebody, that is, NPV (10%) for a given capacity was taken to be this maximum value.

A Note On Cut-off Grades: The cut-off grade is the point at which a distinction can be made between the ore that is processed, and the ore which is considered waste. So for example, if the cut-off grade for a particular mine was 0.3% copper, the ore which had an average grade higher than 0.3% copper would be sent for processing and the rest of the ore which had an average grade lower than 0.3% copper, would then be dumped by the side of the mine as "waste." This relationship between processed ore and waste forms the basis of processing decisions and mining companies spend a considerable amount of time and capital ascertaining the "optimal" cut-off grade which varies from mine to mine.

Changing the value of the cut-off grade will bring about a number of changes in processing and the annual value of the final product. In particular, the trade offs associated with increasing or decreasing the cut-off grade are extremely important in a mining operation. In this study for example, we found that for copper, because a typical coefficient of variation for the grade is low (0.22), the range of influence of the cut-off grade is relatively small compared to the case of gold where increasing or decreasing the cut-off grade has a considerable impact on the size of mineable reserves.

The following were the examples of orebodies, average grades and annual production capacity used:

Copper

(i) Dump leaching for reserves of 50 million tonnes, at an average grade of 1 percent copper with an annual capacity of 3 to 8 million tonnes.
(ii) Dump leaching for reserves of 250 million tonnes, at an average grade of 0.5 percent copper with an annual capacity of 12 to 22 million tonnes.
(iii)Heap leaching for reserves of 50 million tonnes, at an average grade of 1 percent copper with an annual capacity of 3 to 8 million tonnes.
(iv) Heap leaching for reserves of 75 million tonnes at an average grade of 1 percent copper with an annual capacity of 5 to 9 million tonnes.
(v) Heap leaching for reserves of 150 million tonnes at an average grade of 1 percent copper with an annual capacity of 6 to 12 million tonnes.
(vi) Vat leaching for reserves of 150 million tonnes at an average grade of 1 percent copper with an annual capacity of 6 to 12 million tonnes.

Gold

(i) Vat leaching for reserves of 10 million tonnes at an average grade of 3 gm Au/tonne with an annual capacity of 0.5 to 0.9 million tonnes.
(ii) Vat leaching for reserves of 10 million tonnes at an average grade of 4 gm Au/tonne with an annual capacity of 0.5 to 0.7 million tonnes.
(iii)Vat leaching for reserves of 10 million tonnes at an average grade of 5 gm Au/tonne with an annual capacity of 0.5 to 1.0 million tonnes.
(iv) Heap leaching for reserves of 10 million tonnes at an average grade of 3 gm Au/tonne with an annual capacity of 0.5 to 0.9 million tonnes per annum.

5.2.2 Results

Copper

The results of the two dump leaching tests showed that while (i) was economic, having a positive NPV (10%) for all capacities, (ii) was economic only for capacities larger than 14.5 million tonnes per year. For the heap leaching scenarios (iii), (iv) and (v), it was found that they were economic only at ore capacity levels of over 50 mil ion tonnes.

The final computer analysis for copper looked at bacterial vat leaching at 1 percent copper grading of an orebody of 150 million tonnes. However, while the same scenario was successful using bacterial heap leaching (see above), bacterial vat leaching was not economic for copper. Values for the first dump leaching scenario showed the orebody to have a positive NPV for all values. However in the case of the second dump leaching analysis NPV was positive only for values above 14 million tonnes per year. In the case of heap leaching, while the two larger sized orebodies of 75 million and 150 million tonnes were economic at all capacities, the smallest reserve of 50 million tonnes was not economic at all, that is, it had a negative NPV for all capacities. Indeed vat leaching of copper was not economic at all and because of the large negative values obtained, this method of leaching was rejected altogether for copper orebodies.

Gold

Three different scenarios using bacterial vat leaching for different average ore grades were considered. While (i) was uneconomic, (ii) was only marginally economic. However (iii), which considered high grade refractory gold ores of 5 g Au/tonne, proved to be economic. In the case of gold we saw that as the cut-off grade rose the NPV of the orebody rose until a maximum value was reached and then began to slope down. This maximum point is the optimal cut-off point and demonstrates the maximum value of NPV for the project. This value was positive for the highest grade of gold chosen, 5 g Au/tonne, only marginally economic for 4 g Au/tonne and negative at all points for the lower grade, 3 g Au/tonne.

This suggests that heap leaching can be more effective for lower average grades of refractory gold than vat leaching. In contrast, the single analysis using heap leaching showed that it was marginally economic using lower average grades of 3 g Au/tonne.

The results of this analysis, although preliminary, showed that bacterial leaching can indeed be considered a viable technology for certain orebodies depending upon size of reserves, average grades of mineralisation as well as cut off grades. It must however be stressed that in the final analysis, the costs and benefits of bacterial leaching will differ from mine to mine and while in some cases will be considered economic compared to other technologies, for others it may not. What this study does do is provide an example in which bacterial leaching did provide economic benefits for a range of orebodies with differing average grades. The initiative of introducing this new technology as a possible alternative in feasibility analyses must now be taken by the mining community which in some cases is already taking place.

6. Conclusions and Suggestions for Future Research

This study was based on a review of the latest developments in the field of bacterial leaching especially with relation to five metals: gold, silver, copper, manganese and cobalt. While copper and the precious metals, gold and silver have received the most attention so far, applications to other metals such as the two identified above are also progressing.

We reached three major conclusions from this study and these may also provide research areas for the future:

1. With pressure on countries especially developing countries to adjust to changing conditions in the mining industry and international markets, bacterial leaching offers considerable potential. Bacterial leaching offers developing countries the ability to develop their own capabilities in the area of biotechnology. Having developed this capability in bacterial leaching, developing countries can compete with developed countries and among themselves to expand economically, not only in mining but also in other areas where biotechnology has been applied with considerable success.

2. Bacterial leaching is an environmentally sound technology. Mineral extraction processes currently make use of smelters which are not only expensive to construct but are also a major source of environmental pollution. The world has recognised the importance of environmental conservation as is evident from recent developments in industrial countries. Bacterial leaching not only provides an alternative, environmental friendly technology to mining companies in the north who are bound by environmental regulations but also provides developing countries with a new technology which is cheaper than and at least as efficient as smelters while at the same time bypassing some of the environmental damage caused in the north. The new area of biosorption also promotes the use of biotechnology in solid waste treatment substantially reducing pollution from mining and industrial effluents.

3. The results from the economic feasibility analysis for copper and gold bioleaching show that for copper, while dump leaching was economic for lower sized orebodies, heap leaching was successful for orebodies of a larger size. This is an important conclusion, since metal recovery using heap leaching can be significantly higher by optimising leaching conditions than in the case of dump leaching where recovery levels cannot be predicted but are generally lower. Additionally, this is important for developing countries such as Chile, one of the main copper producers, where the size of deposits generally tends to be large (Porphyry copper orebodies in the country range from about 4.6 million metric

tonnes at the El Indio copper mine to 18.5 billion metric tonnes at Chuquicamata, the world's largest copper deposit).

For gold, we can conclude that this preliminary analysis favours the use of heap leaching for lower grades while vat leaching can be used for higher grade ores. Vat leaching which requires optimization in controlled environments is generally considered to be unfavourable for developing countries which may not have access to the optimisation facilities or the higher capital investment associated with this form of bacterial leaching. Heap leaching on the other hand, as already pointed out, can result in metal recoveries of up to 80% when optimised.

6.1. Advantages of Bacterial Leaching for Developing Countries

It is perhaps to developing country metal producers that biotechnology provides the greatest advantages. The technology requires relatively lower capital investment and operating costs are also low when compared to conventional mining. Biotechnology may also prove useful in solving a number of metallurgical problems associated with complex ore deposits, many of them found in developing countries. In this respect it has already demonstrated its potential to extract different metals such as the separation of zinc and lead concentrates from these multimineral deposits.

Research conducted in developing countries has demonstrated the applicability of bacteria to the leaching of copper and refractory gold. Still further potential lies in the refractory deposits of the Pacific rim countries especially Papua New Guinea. For the other metals, research is still in its preliminary stages, however, since a large percentage of both but especially cobalt is produced in developing countries, applications of bacterial leaching to these metals will be especially beneficial to developing countries.

As much of the current bacterial leaching applications are carried out on ore dumps, developing countries which have higher grade ore dumps (less sophisticated technology in developing countries has imposed a higher cut-off grade in mining operations. As a result, ore dumps have a higher metal content in developing countries than similar dumps in developed countries) are in an especially good position to use bacterial leaching technology.

In developing countries the cost of building refining plants is enormous. In building a smelter, the relevant mining authority has to take into consideration all the extra costs such as the cost of transporting ore from mines all over the country to be processed at the smelter. As a result, poorer developing countries tend to export unprocessed minerals to countries which do have the facilities for refining ore (mostly developed countries). One such example is Zaire which ships its raw materials to Belgium to be refined. In this process, the developing country loses the value added from refining the metal. Bacterial leaching, by enabling the production of a purer form of metal at the mine site, again offers an advantage in this respect. Thus optimisation of the leaching process provides developing countries with the opportunity to lower costs, mine a larger range of metals and increase their value added by producing a marketable final product.

Thus biotechnology, although used extensively in industry and agriculture is relatively new to mining. Considerable research still remains to be done to exploit this technology effectively. Despite this, the few commercial applications that have developed over the last few years have demonstrated its effectiveness. Increasing interest on the part of the international conglomerates and governments promises further developments both in research and industrial scale applications of bacterial leaching to the mining industry.

NOTES

1. LeRoux, N. W. (1969).

2. Warhurst, A. C. (1985b), pp 6-7.

3. Harris, L. and J. A. Brierley (1989), pp 301-304.

4. Warhurst, A. C. (1989), pp 6-7.

5. Ibid., pp 8-10.

6. See for example McElroy, R. O. and A. Bruynesteyn (1978) and Hackl, R. P., F. Wright and A. Bruynesteyn (1986).

7. Monhemius, A. J. (1987), p 1.

8. A number of studies have demonstrated the success in using bioleaching for pre treatment of refractory gold. These studies indicate that bacterial leaching has definite advantages over conventional pre treatment methods. See for example:
Hackl, Wright and Bruynesteyn (1986), Hackl, Wright and Brüynesteyn (1987), Lawrence (1987) and Gilbert, Bounds and Ice (1987).

9. Lawrence, R. W. and P. B. Marchant (1988).

10. Norris, P. R. and L. Parrot (1986).

11. Lindstrom E. B. and L. Gunneriusson (1988).

12. Ngubane, A. and A. W. Baecker (1988).

13. Norris, P. R. and D. W. Barr (1988).

14. Murr, L. E., A. E. Torma and J. A. Brierley (eds) (1978).

15. Ehrlich, H. L. (1986).

16. Karavaiko, Chuchalin, Pivovarova, Yemel'yanov and Dorofeyev (1986).

17. Hackl, Wright and Bruynesteyn (1986), p 11.

18. Anon (1987), Mining Journal, October 2, p 629.

19. Marchant (1986).

20. Harris and Brierley (1989), p 302.

21. Baron (1985) and Michot (1986).

22. Anon (1987), "A Golden Future for P.N.G.", *Mining Journal*, February 13, 1987, pp 101-103.

23. Groudev (1986)

24. Suzuki, Lizama and Oh (1987) and Sanmugasunderam, Gould, McCready, Rajan, Beulne and Mainwaring (1987).

25. McCready (1988).

26. Ballester, Gonzales, Blasquez, Mier and Munoz (1988).

27. Ahonen and Tuovinen (1988).

28. Ismay, Rosato and McKinnon (1986).

29. Rossi, Trois and Visca (1986).

30. Miller (1986).

31. Warhurst (1985b), pp 100-103.

32. Anon (1988), *Mining Annual Review*, p 304.

33. Pincheira, et al (1986).

34. Castillo, Herrera, Neuberry, Vargas, Wiertz and Badilla-Ohlbaum (1988).

35. Ismay, Rosato and McKinnon (1986).

36. Choi and Hopkin (1988).

37. Khinvasura and Agate (1988).

38. Bosecker (1987), p 367.

39. Karavaiko et al (1988), p 306.

40. Murr, Torma and Brierley (eds) (1978), p 278.

41. Karavaiko et al (1988), p 307.

42. Ibid, p 307.

43. Anon (1989), "Metals and Minerals Review -- 1989: Cobalt", *Mining Annual Review*, pp C68-C69.

44. Alexander and Street (1982).

45. Miller, Huberts and Livesey-Goldblatt (1986), p 23.

46. Brierley, Brierley and Goyak (1986), Kuyucak and Volesky (1987) and Kuyucak and Volesky (1988).

47. Kuyucak and Volesky (1988).

48. Treen-Seers, Martin and Volesky (1986).

49. Gadd, While and de Rome (1988).

50. Gee and Dudeney (1988).

51. Byerley, Scharer and Rioux (1989).

52. Townsley, Ross and Atkins (1986).

53. Brierley, et al. (1986).

54. Karavaiko, et al (1988), pp 347-349.

55. Acharya and Spencer (1989).

56. Hackl, Wright and Bruynesteyn (1986) and Hackl, Wright and Bruynesteyn (1987).

57. Gibbs, Errington and Pooley (1985).

58. Acharya and Spencer (1989).

59. Gilbert, Bounds and Ice (1987).

60. Murr, Torma and Brierley (eds) (1978), pp 441-462.

61. Acharya and Spencer (1989).

62. O'Hara (1980), Straam Engineers Inc. (1978) and US Bureau of Mines (1987).

REFERENCES

Abelson, Philip H. (1988) "Improved Efficiency of US Copper Production" *Science*, 11 November, Vol. 242, No. 4880, p. 837.

Acharya, R. and R. Spencer (1989), "Biotechnology and the Mining Industry: The Bacterial Connection," *IFIAS Biopolicy Series*, Forthcoming.

Ahlness, J.K. and M.G. Pojar (1983), "In Situ Copper Mining in the United States: Case Histories of Operations," *US Bureau of Mines, Information Circular* No. 8961.

Ahonen, L. and O. H. Tuovinen (1988), "Percolation Leaching of a Sulfide Ore Material in Relation to PH and Redox Potential," *Biohydrometallurgy: Proceedings of the International Symposium*, Warwick; P.R. Norris and D.P. Kelly (Eds), pp 504-505; (London: Science and Technology Letters).

Alexander, W. and A. Street (1982), *Metals in the Service of Man*, (New York: Penguin Books).

Ballester, A., F. Gonzalez, M. Blazquez, J.L. Mier and J. Munoz (1988), "Spanish Sulphides: Attack by Bioleaching." *Biohydrometallurgy*, pp 512-513.

Banks, Ferdinand E. (1974), *The World Copper Market: An Economic Analysis*, (Cambridge: Ballinger Publishing Company).

Baron, J.L., "Hydrometallurgy, Project 236: Bacterial Leaching (1985),"*Sixteenth Annual Report of the Institute of Mining Research*, University of Zimbabwe, No. 56, K.A. Viewing (Ed).

Bosecker, K. (1986), "Leaching of Laterite Nickel Ores with Heterotrophic Microorganisms", *Fundamental and Applied Biohydrometallurgy: Proceedings of the Sixth International Conference on Biohydrometallurgy*, Vancouver, August 21-24, 1986; R. W. Lawrence, R. M. R. Branion and H. G. Ebner (eds) (Amsterdam: Elsevier), pp 367-382.

Brierley, C. L. (1988), "The Commercial Development of Metals and Minerals Technology," in *Biohydrometallurgy*, pp 15-24.

Brierley, J. A., C. L. Brierley and G.M. Goyak (1987), "AMT-BIOCLAIM: A New Wastewater treatment and Metal Recovery Technology," *Fundamental and Applied Biohydrometallurgy*, pp 291-303.

Byerley, J. J., J. M. Scharer and S. N. Rioux (1989), "Possible Applications of Microorganisms for Recovery of Rare Metals from Aqueous Solutions," *Precious and Rare Metal Technologies: Proceedings of a Symposium on Precious and Rare Metals*, Albuquerque, NM, USA, April 6-8 1988; (eds) A. E. Torma and I. H. Gundiler (Amsterdam: Elsevier), pp 317-331.

Campbell, M. C., H. W. Parsons, A. W. Jongejan, V. Sanmugasunderam and M. Silver (1985), "Biotechnology for the Mining Industry," *Canadian Metallurgical Quarterly*, Vol. 24, No. 2, pp 115-120.

Castillo, J., M. Herrera, L. Herrera, H. Neuberry, T. Vargas, J. Wiertz and R. Badilla-Ohlbaum (1988), "Kinetic Column Leaching Model for Copper Containing Ores," *Biohydrometallurgy*, pp 184-196.

Choi, P. C. and W. Hopkin (1988), "Percolation Leach Test on Copper Ore from Cerro Colorado, Panama," *Biohydrometallurgy*, pp 197-210.

Copper Development Association and Commodities Research Unit (1980), "Present and Future Markets for Copper" Second International Conference, Royal Garden Hotel, London, 15 October.

Ehrlich, H. L. (1986), "Bacterial Leaching of Silver from a Silver-Containing Mixed Sulphide Ore by a Continuous Process," *Fundamental and Applied Biohydrometallurgy*, pp 77-78.

Gadd, G. M., C. While and L. de Rome (1988), "Heavy Metal and Radionuclide Uptake by Fungi and Yeasts," *Biohydrometallurgy*, pp 421-435.

Gee, A. R. and A. W. L. Dudeney (1988), "Adsorption and Crystallisation of Gold at Biological Surfaces," *Biohydrometallurgy*, pp 437-451.

Gibbs, H. E., M. Errington and F. D. Pooley (1985), "Economics of Bacterial Leaching," *Canadian Metallurgical Quarterly*, Vol. 24, No. 2, pp 121-125.

Gilbert, S. R., C. O. Bounds and R. R. Ice (1987), "Comparative Economics of Bacterial Leaching and Roasting for an Auriferous Pyrite Concentrate," *Proceedings of the Third Annual Meeting of Biominet*, August 20-21, 1986, Toronto, Canada; R. G. L. McCready (Ed), CANMET, pp 53-70.

Gluschke, W. et al (1979), *Copper: The Next Fifteen Years*, A United Nations Study, (Washington DC.: D. Reidel Publishing Co).

Gocht, W.R. et al (1988), *International Mineral Economics: Mineral Exploration, Mine Valuation, Mineral Markets, International Mineral Policies*, (Springer Verlag).

Gordon, Robert B., T. C. Koopmans, W. D. Nordhaus and B. J. Skinner (1987), *Toward A New Iron Age? Quantitative Modelling of Resource Exhaustion* (Cambridge: Harvard University Press, 1987).

Groudev, S. N. (1986), "Continuous Bacterial Leaching of Copper Sulphide Concentrates," *Fundamental and Applied Biohydrometallurgy*, pp 43-50.

Hackl, R. P., F. Wright and A. Bruynesteyn (1986), "A New Biotech Process for Refractory Gold/Silver Concentrates," Paper presented at *Biotechnology for Gold Industry Symposium*, 25th Annual Conference of Metallurgists, Toronto, Ontario, August 17-20.

Hackl, R. P, F. Wright and A. Bruynesteyn (1987), "A New Biotech Process for Refractory Gold-Silver Concentrates," *Third Annual Meeting of Biominet*, pp 71-90.

Harris, L. and J. A. Brierley (1989), "Biotechnology," *Mining Magazine*, October, 1989, pp 301-304.

Holmes, D. S., J. R. Yates and J. Schrader (1988), "Mobile, Repeated DNA Sequences in T. ferrooxidans and Their Significance for Biomining," *Biohydrometallurgy*, pp 153-160.

Hotelling, H. (1931), "The Economics of Exhaustible Resources" *Journal of Political Economy*, 39, pp 137-175.

Houtman, Cas (1985), "Base Metals----Prosperity or Adversity?" *South African Mining World*, pp 53-56.

IBRD (1986), "The World Copper Industry: Its Changing Structure and Future Prospects" Kenji Takeuchi, John E. Strongman and Shunichi Maeda. World Bank Staff Commodity Working Papers, No. 15; (Washington DC: IBRD).

IMF (1988),*International Financial Statistics*, (Washington DC: International Monetary Fund).

Ismay, A., L. Rosato and D. McKinnon (1987), "Engineering Prefeasibility for in-place Bacterial Leaching of Copper," *Fundamental and Applied Biohydrometallurgy*, pp 191-213.

Jerez, C. A., I Peirano, D. Chamorro and G. Campos (1986), "Immunological and Electrophoretic Differentiation of T. ferrooxidans Strains," *Fundamental and Applied Biohydrometallurgy*, pp 443-456.

Kaonides, Lakis (1989), "Advanced Materials and Primary Commodities: A review of recent scientific and technological developments and their implications for industrial policy and strategy," prepared for the Expert Group Meeting on Prospects for Industrialisation Policies In Developing Countries Taking Into Account the Impact of Developments in the Field of New and High Technologies, First Draft, United Nations Industrial Development Organisation, Vienna, Austria 4-7 April.

Karavaiko, G. I., L. K. Chuchalin, T. A. Pivovarova, B. A. Yemel'yanov and A. G. Dorofeyev (1986), "Microbial Leaching of Metals from Arsenopyrite Containing Concentrates," *Fundamental and Applied Biohydrometallurgy*, pp 115-126.

Karavaiko, G. I., G. Rossi, A. D. Agate, S. N. Groudev and Z. A. Avakyan (eds) (1988), *Biogeotechnology of Metals: Manual*, Sponsored by UNEP and the USSR Commission for UNEP; (Moscow: Centre for International Projects GKNT).

Kelly, D. P. (1988), "Evolution of the Understanding of the Microbiology and the Mineral Leaching Habitat," *Biohydrometallurgy*, pp 3-14.

Khinvasura, N. J. and A. D. Agate (1988), "Bioreactor Leaching of Chalcopyrite Concentrate from Mosaboni, India," *Biohydrometallurgy*, pp 297-303.

Kuyucak, N. and B. Volesky (1987), "Recovery of Gold by Biosorption," *Third Annual General Meeting of Biominet*, pp 171-172.

Kuyucak, N. and B. Volesky (1987), " New Algal Biosorbent for a Gold Recovery Process," *Biohydrometallurgy*, pp 453-463.

Kuyucak, N. and B. Volesky (1988), "Recovery of Cobalt by a New Biosorbent," *CIM Bulletin*, February, pp 95-99.

Lawrence, R. W. (1987), "The Potential of Thermophilic Bacteria in the Pretreatment of Refractory Gold Ores," *Third Annual General Meeting of Biominet*, 1986, pp 75-102.

Lawrence, R. W. and P. B. Marchant (1988), "Comparison of Mesophilic and Thermophilic Oxidation Systems for the Treatment of Refractory Gold Ores and Concentrates," *Biohydrometallurgy*, pp 359-374.

LeRoux, N. W. (1969), "Mining With Microbes," *New Scientist*, Vol. 43, No. 668 (25 September), 13, 16.

LeRoux, N. W. (1988), "Visit to India 1988, British Council, August 1988," Warren Spring Laboratory, Consultancy Report, 1988.

Lindstrom, E. Borje and L. Gunneriusson (1988), "Semi-Continuous Leaching of Arsenopyrite with a Sulfolobus Strain at 70 degrees celsius," *Biohydrometallurgy*, pp 525-527.

Marchant, P. B. (1987), "Commercial Piloting and the Economic Feasibility of Plant Scale Continuous Biological Tank Leaching at Equity Silver Mines Limited," *Fundamental and Applied Biohydrometallurgy*, pp 53-75.

McCready, R. G. L. (1988), "Progress in the Bacterial Leaching of Metals in Canada," *Biohydrometallurgy*, pp 25-34.

Michot, L. (1986), "Hydrometallurgy, Project 236: Bacterial Leaching," *Seventeenth Annual Report of the Institute of Mining Research, University of Zimbabwe*, No. 62; K. A. Viewing (Ed).

Mikesell, Raymond F. (1988), *The Global Copper Industry: Problems and Prospects*, (London: Croom Helm).

Miller, P. C. (1987), "Large-Scale Bacterial Leaching of a Copper-Zinc Ore in situ," *Fundamental and Applied Biohydrometallurgy*, pp 215-239.

Miller, P. C., R. Huberts and E. Livesey-Goldblatt (1986), "The Semi-continuous Bacterial Agitated Treatment of Nickel Sulphide Material," *Fundamental and Applied Biohydrometallurgy*, pp 23-42.

Metallgesellschaft Various Issues in 1987 and 1988.

Mining Annual Review 1984-1989.

Mining Journal 1984-1989.

Mining Magazine 1984-1989.

Monheimus, A. J. (1987), "Recent Advances in the Treatment of Refractory Gold Ores," Paper presented at the *Second Meeting of the Southern Hemisphere on Mineral Technology*, Rio de Janeiro, Brazil, 25-29 May.

Murr, L. E., A. E. Torma and J. A. Brierley (eds) (1978), *Metallurgical Applications of Bacterial Leaching and Related Microbial Phenomena*, (New York: Academic Press).

Ngubane, A. and A. W. Baecker (1988), "Thermophilic Pyrite Leaching by Sulfolobus brierleyi," *Biohydrometallurgy*, pp 528-529.

Norris, P. R. and L. Parrot (1986), "High Temperature Mineral Concentrate Dissolution with Sulfolobus," *Fundamental and Applied Biohydrometallurgy*, pp 355-365.

Norris, P. R., D. W. Barr and D. Hinson (1988), "Iron and Mineral Oxidation by Acidophilic Bacteria: Affinities for Iron and Attachment to Pyrite," *Biohydrometallurgy*, pp 43-59.

Norris, P. R. and D. W. Barr (1988), "Bacterial Oxidation of Pyrite in High Temperature Reactors," *Biohydrometallurgy*, pp 532-536.

O'Hara, T. A. (1980), "Quick Guides to the Evaluation of Ore Bodies," *CIM Bulletin*, February, 1980, pp 29-32.

Pincheira, A. et al (1986), "Lixiviacion Bacteriana de Minerales Sulfurados de Cobre de Baja Ley" *Minerales: Instituto de Ingenieros de Minas de Chile*, Vol. 41, No. 174, Abril, Mayo, Junio, pp 13-20.

Radetzki, Marian (1983), "Long-run Price Prospects for Aluminium and Copper" *Natural Resources Forum*, Vol. 7, No. 1, pp 23-36.

Radetzki, Marian (1986), "Structural Change in World Copper Supply," *Natural Resources Forum*, Vol. 10, No. 3, pp 281-291.

Radetzki, Marian (1988), "Structural Change in World Metal Industries" *Mining Magazine*, January, pp 29-33.

Rawlings, D. E., R. Sewcharan and D. R. Woods (1988), "Characterisation of a Broad-Host-Range Mobilizable T. ferrooxidans Plasmid and the Construction of Thiobacillus Cloning Vectors," *Fundamental and Applied Biohydrometallurgy*, pp 419-427.

Rawlings, D. E., I-M Pretorius and D. R. Woods (1988), "A Comparative Sequence Analysis of T. ferrooxidans Nitrogen Metabolism Gene Structure," *Biohydrometallurgy*, pp 161-174.

Rossi, G., P. Trois and P. Visca (1987), "In situ Pilot Semi-Commercial Bioleaching Test at the San Valentino di Predoi Mine (Northern Italy)," *Fundamental and Applied Biohydrometallurgy*, pp 173-189.

Sanmugasunderam, V., W. D. Gould, R. G. L. McCready, S. Rajan, M. Beulne and P. Mainwaring (1987), "Bacterial and Chemical Leaching of Complex Sulphide Ores," *Third Annual General Meeting of Biominet*, pp 103-116.

Sarkar, B. C. (1988), "An Integrated System for Geology - Controlled Geostatistical Evaluation," Ph.D. thesis, London University.

Spencer, R. (1987a), "Financial Evaluation, Part I: Value Measurement," *Mine and Quarry*, 16, No. 3, pp 60.

Spencer, R. (1987), "Financial Evaluation, Part II: Application of Value Measurements," *Mine and Qua.ry*, 16, No. 4, pp 44.

Straam Engineers Inc. (1978), "Capital and Cost Estimating Handbook, Mining and Benefication of Metallic and Non-Metallic Minerals except Fossil Fuels in United States and Canada," Arcadia, California. Prepared for the Bureau of Mines, California, July 1978.

Sullivan, D. E., Thomas, P. R. and Yaremchuk, E. M. (1987), "International Mining Cost Indexation System, Indexes for 96 Countries," *US Bureau of Mines, Information Circular* 9158

Suzuki, I., H. M. Lizama and J. K. Oh (1987), "Bacterial Leaching of a Complex Sulphide Ore," *Third Annual General Meeting of Biominet*, pp 127-146.

Tilton, John E. (1988), "The New View of Minerals and Economic Growth" Working Paper 88-10, Colorado School of Mines, Department of Mineral Economics, Golden, Colorado, August, 1988.

Townsley, C. C., I. S. Ross and A. S. Atkins (1987), "Biorecovery of Metallic Residues from Various Industrial Effluents Using Filamentous Fungi," *Fundamental and Applied Biohydrometallurgy*, pp 279-289.

Treen-Sears, M. E., S. M. Martin and B. Volesky (1987), "Control of Rhizopus Biosorbents Quality during Propagation," *Fundamental and Applied Biohydrometallurgy*, pp 305-308.

UNIDO (1984), "The Application of Biotechnology in Developing Countries: The Case of Mineral Leaching, with particular reference to the Andean Pact Copper Project" By Alyson C. Warhurst, (Vienna: UNIDO, March).

US Bureau of Mines (1987), "Bureau of Mines Cost Estimating System Handbook, Part 2 Mineral Processing," *US Bureau of Mines, Information Circular*, 9143.

Visca, P., P. Valenti and N. Orsi (1987), "Characterisation of Plasmids in T. ferrooxidans Strains," *Fundamental and Applied Biohydrometallurgy*, pp 429-441.

Warhurst, A. C. (1985a), "The Potential of Biotechnology for Mining in Developing Countries: The Case of the Andean Pact Copper Project," D. Phil. Thesis, Science Policy Research Unit (SPRU), University of Sussex, Brighton, October 1985.

Warhurst, A. C. (1985b), "Biotechnology for Mining: The Potential of an Emerging Technology, The Andean Pact Copper Project and Some Policy Implications," *Development and Change*, Vol. 16, pp 93-121.

Warhurst, A. C. (1989), "The Potential of Biotechnology In Minerals Development," Paper presented at *IFIAS-ACTS-UNEP International Symposium on Biotechnology for Sustainable Development*, February-March, UNEP Headquarters, Nairobi, Kenya.

Yates, J. R. and D. S. Holmes (1987), "Construction and Use of Molecular Probes to Identify and Quantitate Bioleaching Microorganisms," *Fundamental and Applied Biohydrometallurgy*, pp 409-418.