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Biohydrometallurgy| The technological transformation of the mining industry for environmental protection

Keith H. Debus

The University of Montana

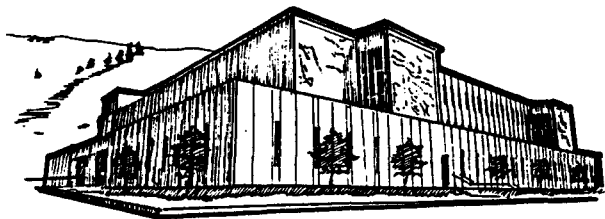
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Biohydrometallurgy:
The Technological Transformation
of the Mining Industry
for
Environmental Protection

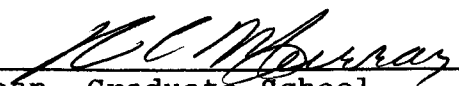
by
Keith H. Debus

Presented in partial fulfillment of the requirements
for the degree of
Master of Science
University of Montana
1990

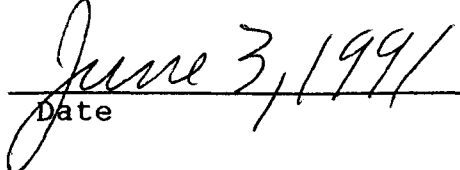
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I. Introduction and Overview

Archeological evidence indicates that the mining and smelting of metal ores has been carried out in Western Civilization since at least 4500 B.C. Although this discovery at Timna, Israel may seem unremarkable, it has dramatically altered archeologists' conception of how early man obtained metals for tool making and ornament. Previously, it had been believed that all metals at that time were obtained in their native form or naturally occurring metallic form. This distinction is critical as native metals require little in the way of technology before being formed. Ancient people were believed to have found metallic rocks and simply hammered them into shape. Instead we now know that these early civilizations identified ore bodies where metal was combined chemically with other elements, dug them from the earth and processed or "smelted" these ores with fire to obtain the metal values from the valueless rock. This site is often cited as an example of how advanced these early civilizations were technologically.

Conversely, one might interpret these findings as signifying how primitive the mining and minerals industry is. The techniques of the mineral industry have changed little in the intervening 6500 years. The global mining industry still largely digs rock from the ground and smelts the ore to obtain the valuable metals. This simple technique has served Western civilization extraordinarily well provided three conditions: high ore grade, inexpensive energy, and dormant concerns for the environmental degradation.

As the mining industry peers forward into the 1990's, it is likely to find that none of these three conditions will prevail. If the industry were to glimpse itself in the 21st century it would likely see an industry more closely identified as a biotechnology industry than the present configuration of earth moving and rock burning. Accordingly, the scientists and engineers are reacting with some haste to develop biotechnology for the recovery of low grade metalliferous ores with little energy consumption and minimal environmental disturbance.

Quantitative Expansion

Initially, early civilizations mined and smelted what the mining industry now would refer to as very high grade ore, or simply put, rock that contains a high percentage of metal by volume. As the centuries and millennia passed, these high grade ores were steadily exhausted to be replaced by metal ores that continually contained less metal and more rock. This

embryonic industry needed to improve their techniques to mine economically these lower grade ores. By and large, though, the ancient techniques remained unchanged right up to the present day. To obtain the improvements and efficiencies necessary to produce economically the metal from these leaner ores, the industry increased the scale of its activities to capture what economists refer to as "economies of scale."

These efforts to increase the scale of the mining operations in order to reduce production costs per pound of metal led to the development of open-pit mining that predominates in the industry today. This method seeks to move enormous volumes of rock to obtain a small amount of metal disseminated throughout the rock. This increase in the scale of mining has led to a concomitant increase in the magnitude and scale of the environmental degradation by this basic industry of industrial society. The open-pits of the modern industry are measured in square miles (some pits are as large in area as a medium-sized American city) and the wastes they generate in millions or billions of tons. Such enormous pits-- setting aside their aesthetic debasement-- are a source of water contamination. As ground water and precipitation percolate through these pits and ores now open to the atmosphere it becomes contaminated with acid and metals. The same contamination takes place in the hundreds of square miles of waste dumps throughout the mining industry. Furthermore, we now know that some of this environmental degradation will continue for centuries or even millennia as evidenced by the Roman lead-zinc mines in Wales that are still a source of water contamination problems today, nearly two thousand years since their last activity. Moreover, huge smelters that separate sulfur from the metal expel gases and particulate matter laden with metals and sulfur dioxide (the copper industry produces two tons of sulfur gases for every ton of metal produced), the precursor of acid rain as it is carried downstream in the air shed (undoubtedly, this particular environmental effect has improved dramatically in recent years but only relative to its dismal performance in previous years). The quantitative expansion of the mining techniques of the ancients by the modern metal mining industry has, unfortunately, been paralleled by its environmental degradation.

G.W.F. Hegel wrote in "Philosophical Propaedeutics" that a quantitative change, if large enough, could bring about a qualitative metamorphosis. Although Hegel was not specifically referring to technology, it is just as appropriate in the arena of technological change as any other. The metal mining industry is an exquisite example of this point. It now appears now that the metal mining industry has arrived at that juncture where its quantitative expansion of its technology has advanced so far that it is now bringing about a

qualitative change in its techniques and means of production. Such a change is beginning to alter the industry's conceptual paradigm concerning its mode of production and with it, its impact upon the natural environment from which it derives its riches. Such a change should be both applauded and advanced.

Biotechnology in the Mining Industry

In an industry that measures its volume of material handled in billions of tons per year and barely blinks at the challenge of actually moving a mountain, microscopic organisms too small to see with the human eye are the foundation of a qualitative transformation of the techniques used to extract and process metals. In the last decade, this transformation has accelerated to the point that some observers of the industry credit these techniques with the salvation of the U.S. copper mining industry and some visionary enthusiasts are describing the future of the mining industry as that of a biotechnology-materials industry.

In contrast to the fanfare trumpeting the milestones of the pharmaceutical and agricultural biotechnology industry, biotechnology has been quietly making inroads into the metal mining and processing industry. In 1989, over 30% of the copper produced in the U.S. was a result of a biochemical process catalyzed by a ubiquitous microorganism that biologists refer to as Thiobacillus ferrooxidans. Biohydrometallurgy, the term most often used by scientists to describe this field of biology and metals, has not been limited to copper leaching. In the 1970's, uranium was first commercially biologically leached from abandoned mine workings in Canada. Most exciting for the mining industry presently are developments in the biological oxidation of refractory gold ore. This microbiological process is helping the gold mining industry to obtain higher recoveries of gold from their ore. Two such commercial plants have operating in South Africa since the mid-1980's and this year, U.S. Gold is now completing in Nevada the first commercial scale refractory gold ore bio-oxidation plant in North America.

Biohydrometallurgy is also being applied to environmental problems that involve metals and minerals. Intensive research continues at various locations across the U.S. and the globe to use microorganisms to efficiently and inexpensively remove sulfur from coal before it is burned in power plants. This would sharply reduce sulfur dioxide emissions and acid rain. Significant research continues and several commercial applications have been initiated using the metal trapping and concentrating capabilities of some bacteria, algae, and fungi to remove and recycle metals from industrial waste water. Homestake Mining began to utilize a biological cyanide treatment system in 1983 whose performance has exceeded

expectations and legal environmental mandates from the State of South Dakota. Among the most promising applications is the culturing and growing of sulfate reducing bacteria that will reverse the oxidation process that created the acid and released the metals into water. Boojum Research Ltd. of Toronto, Ontario has developed such sulfate-reducing systems at two (2) Canadian mines that re-mineralize the sulfur and metals before the water leaves the mine area. Such "ecological engineering" of the wastes from mines may hold a key to the nature of the 21st century mining. This is just the beginning of the potential applications.

The Industry's Problems

The U.S. mining industry has been plagued by recurring problems in recent years that have hindered their competitiveness and ultimately threaten their viability. Ore grade is gradually and inexorably declining in U.S. ore bodies. Understandably, mining companies tend to mine first that ore that is richest in the desired metal and move to the lower grade material as the high grade ore is exhausted. Occasionally, new deposits of high grade ore are discovered, but the U.S. is well explored and the effect of such rare discoveries is more than offset by the continued operations at well developed sites. For instance, average ore grade in the U.S. copper industry has steadily dropped from above 6% in 1880 to the present 0.6%. Such a drop of one order of magnitude has necessitated the changes in scale of mining operations to remain economically feasible.

The industry had also grown dependent upon inexpensive and abundant energy. Despite recent improvements by the industry, metal mining is very energy intensive. For example, the production of one ton of copper in the U.S. by conventional means requires the consumption of over 100 million BTU's energy. Furthermore, approximately 50% of this energy is consumed moving and crushing rock that is 99.4% waste on average. The industry is expending tremendous amounts of energy moving rock with no value. This rock has always been removed with the metal, but the viability of using techniques that require such large material movements and concomitant waste production has been diminished by the falling ore grade, higher energy prices and increased understanding of the long-term environmental effects.

Public interest has grown increasingly concerned about the metal mining industry's record of environmental disturbance. The metal mining industry in the U.S, now is dependent upon moving entire mountains or creating tremendous craters in the earth to obtain the necessary metals. These open pits--made necessary by the declining ore grade--tend to create water contamination problems as the ore and waste tend to leach acid

and heavy metals such as arsenic into area ground and surface waters. The magnitude of the waste from this industry has a tendency to overwhelm those unfamiliar with its scale. For every pound of copper produced by conventional means in the U.S., the industry produces 198 pounds of waste. The U.S. industry alone produces hundreds of millions of tons of waste per year. Furthermore, the smelting of these ores creates air pollution problems as they emit sulfur dioxide and other compounds into the atmosphere. This problem alone led to the industry spending billions of dollars to contain their sulfur emissions in the 1970's and resulted in the closure of several large smelters that could not make the changes profitably (Today, a large amount of U.S. ore is shipped to Korea and Japan for smelting).

The convergence of these three factors in the 1970's lead to the near demise of the copper industry in the U.S. These factors, combined with the global recession of 1981-82 and worldwide over production, sent copper prices plunging from a high of \$1.45/lb. in 1980 to just \$.58/lb. by 1985. Meanwhile, 28 copper mines closed in the U.S. as uneconomical and for the first time in a century the U.S. abdicated its role as the world's largest copper producer. U.S. mine capacity dropped to 65% and the industry laid off over 35,000 employees to reduce expenses. The nation's largest copper producers sustained losses of a magnitude seldom seen before in this industry. Asarco lost \$384 million between 1982-85, Phelps Dodge lost \$400 between 1982-84, Kennecott lost over \$600 million between 1982-85, and Anaconda, once the nation's largest copper producer, went out of business. By 1985 even the most optimistic observers of the U.S. industry were beginning to number its days. The pain this industry was experiencing only emphasized that the industry's techniques were anachronistic. Their means of production had to change dramatically, not merely incrementally. Such a need was foreseen as early as 1975 by Sir Ronald Prain, chairman for 22 years of the British copper mining company RST Group, when he explained in Copper:the Anatomy of an Industry:

"Already we are mining large tonnages of ore at a grade of 0.4 per cent... The copper industry is therefore ready for... (a) technological breakthrough..."

The industry's very survival compelled a "technological breakthrough." Surprisingly, the breakthrough came from well-known but little understood technology applied with modern tools.

A technique from the past

The first recorded documentation of the commercial utilization of bioleaching occurred in 1752 at the famous Rio

Tinto mine in Spain. Rio Tinto had been a major source of copper for the Roman Empire. Due to the thousands of years of mining at this site, waste rock--known as gangue in the industry--is piled near the mine for several surrounding miles. In 1752, a mining engineer noticed that the water running out and over of these waste dumps was colored a reddish brown. Such an event is less than spectacular at a copper mine as the water from copper mining sites quite typically takes on the color of the red metal. What made this chance happening so portentous is that this engineer noted that as these waters, when intercepted by some scrap iron left lying on the ground, coated the iron with a reddish brown film. He then found that this film could easily be removed with a fingernail and after assaying it found that it was 80-90% copper. Thus began the long circuitous route of the use of microorganisms in the recovery and processing of metals.

The copper precipitate found on the scrap iron at Rio Tinto was what has now come to be known as "cement" copper. As the melting snows and rain percolated through these mining waste dumps, still containing small amounts of copper unrecoverable by conventional techniques, they provided Thiobacillus ferrooxidans the water necessary for their metabolic processes. These organisms, known as acidophilic, autotrophs by microbiologists, are capable of catalyzing the oxidation of sulfide minerals and utilizing the energy released in the reaction. This oxidation process then separates the copper from the sulfide constituent resulting in sulfate and ions of iron and copper. The sulfate then combines with the water to form sulfuric acid, H_2SO_4 . This sulfuric acid is capable of keeping the copper ions in solution (accounting for the reddish brown color of the water) and the sulfuric acid and copper ions then percolate out of the dump. When the solution pregnant with copper was intercepted by the scrap iron, the copper ions precipitates out onto the surface of the iron where it can be removed simply by washing or scraping the scrap iron.

Today this simple process remains largely unchanged with the exception that the industry is more purposeful in its practice. Now sulfuric acid is pumped to the top of a heap or dump and sprayed over the ore. These organisms are acidophilic--acid loving-- and do their work best at a pH of between 1 and 2. When the pregnant solution is recovered the industry has now adopted what is referred to as solvent extraction techniques to remove the copper ions from the solution. Previously, scrap iron had been used, but the expense of scrap iron became a considerable cost component in the recovery of this copper precipitate. Solvent extraction has proved to be very effective and very inexpensive with reports of the average cost of production by bioleaching and solvent extraction-electrowinning as low as \$.25/lb.

(conventional techniques average about \$.60/lb. and copper presently sells for over \$1.00/lb.).

This technique was first utilized in North America commercially in 1907 at a since abandoned copper mine in British Columbia, Canada. By the decade of the teens, it was rapidly being adopted at nearly all the large copper mines in the U.S. as a means of supplementing copper production from these otherwise useless dumps. It should be noted here that at that time the mining industry had little or no understanding of the process but simply understood that if water were poured over the dumps, the water that issued from the bottom of the dumps was laden with copper. They later found that when sulfur was added to the water, creating sulfuric acid, copper production was enhanced. Thus, this method came to be known in the mining industry as "acid leaching."

It remained for Colmer and Hinkle in 1947 to first identify the organism responsible for this production technique. Initially, their work sought an explanation of the phenomena known as acid mine drainage. Acid mine drainage results from water percolating through inactive mines and running out with a low pH and laden with metals. They attributed this process to the oxidation of pyrite in these mines by Thiobacillus. By 1958, Bryner et al identified the same organism, Thiobacillus ferrooxidans, as capable of oxidizing pyrite (FeS) and copper sulfide minerals (i.e., covellite (CuS), chalcopyrite (Cu₂S), bornite (Cu₅FeS₄), etc). This early work was followed by research on other metallic ores and in many cases biological leaching was possible.

Although the use of bioleaching of copper ores grew in the post war era, it did so very slowly. Mining companies considered their leach operations a bit like an unwanted stepchild. Although this technique contributed billions of dollars to the bottom line of these companies, they returned little of it back in the way of research and development.

The Industry Recovery

The industry recovered from this episode of near liquidation determined to reduce costs to a minimum. Among the first things that many did was expand their bioleaching operations. Improvements in the engineering of this process and improved copper precipitation techniques--solvent extraction--had reduced the average cost of production of bioleached copper to less than \$.30 in the intervening years. The average cost of production is a result of lower initial capital costs, lower energy consumption, and greater labor productivity. Simultaneously, the industry's environmental impact has been reduced as the ore from bioleaching need not be smelted.

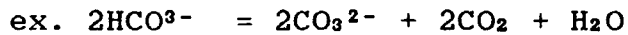
Beginning in 1985 and continuing today the industry has invested heavily into bioleaching-solvent extraction technology and have reduced the average cost of producing copper in the U.S. to less than \$.60 compared to \$.90/pound in 1980. One producer, Phelps Dodge, the nation's largest copper producer and among the most aggressive users of bioleaching techniques, expects to be producing over half of their copper by bioleaching by 1993 at less than \$.30/lb, one-third of the cost of copper production a decade ago.

Disadvantages of Biological mineral processes

Despite biohydrometallurgy's advantages over conventional mining and processing techniques, its commercial adoption has been hampered primarily by its slow rate of recovery of metal values. Conventional processes can recover metal values from an ore body in a matter of months or years, depending upon its size and the level of resources applied to production. Biological metal recovery is relatively slow as it is currently practiced and this has hampered its adoption at several mining sites. In any business, time is money, therefore as time progresses before the metal can be recovered and sold to generate a cash flow, the smaller the present value of the cash flow. At some sites where both techniques have been fully evaluated, biological techniques have often been found to be less expensive than conventional techniques, but the timing of their cash flows has been the primary factor hindering their adoption. Consequently, biohydrometallurgical processes have been thought to be economically feasible only with very low-grade ore where conventional techniques are deemed inappropriate.

The other major impediment to the further application of biological mining has been the lack of adequate and effective particle production techniques. Biological processes are faster and more effective the greater the surface area of the rock. The mining industry uses a variety of methods of particle production, but the primary method remains the use of explosives and the crushing and grinding by rollers and steel grinding balls. These crude and blunt technique haven't changed much since the early fire-setting (rock fracturing) and hammering (crushing and grinding) of the ancient miners except in scale and sophistication. Blasting is inadequate to gain full utilization of in-situ ore bodies, particularly in new previously unmined ore bodies. For biological metal extraction techniques to achieve their full potential, a technique of precisely shattering large ore bodies with innumerable tiny fractures. This greater surface area increases interaction between the microorganisms and the mineral.

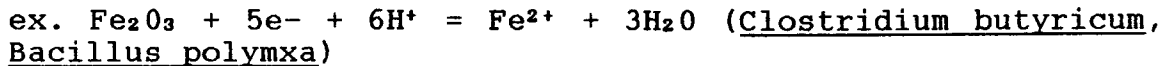
Cyanobacteria and algae can oxidize metals by production of alkali and/or oxygen in photosynthesis.



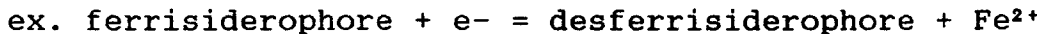
Metal reduction

Enzymatic

Some prokaryotes can use metallic compounds as terminal electron acceptors in respiration in place of oxygen.



Most microbes living at or near neutral pH require iron and can take it up only if chelated by a siderophore. Once taken up, the iron is released from its siderophore by reduction. In a few instances the siderophore may be hydrolyzed before the iron is reduced and released from the siderophore.

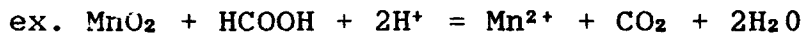


Metallic ions may be reduced to a less toxic form.



Non-enzymatic

Oxidized forms of metals may be reduced by metabolic products which act as reductants.



Metal chelation

By production of metabolic products which can act as chelators

ex. a siderophores of hydroxamate, catechol, or mixed type (affinity coefficient for FeIII is $K_a = 10^{38}$ to 10^{52})

Metal Methylation

Some bacteria have the ability to methylate Hg^{2+} , Sn^{2+} , Pb^{2+} , Cd^{2+} , AsIII, Se^{2-} , Te^{2-} (Hallas et al., 1982; Iverson and Brinckman, 1978; Summers and Silver, 1978)

Metal sorption

Bacterial cell wall

It has been shown that specific components of the bacterial cell wall can bind metal ions. In Bacillus subtilis it is mainly the peptidoglycan, whereas in B. lichenformis it is teichoic and teichoronic acids (Beveridge and Murray, 1980; Beveridge et al., 1982).

In Escherichia coli it is the polar head groups of the constituent membranes and the peptoglycan layer (Beveridge and Koval, 1981). The first two organisms are gram positive whereas E. coli is gram negative.

Bacterial slimes

Slime produced by the bacterium Zoogloea ramigera has been shown to be able to bind metal ions (Friedman and Dugan, 1968).

Metal transport

Microorganisms accumulate some metals intracellularly, in part because they need these metals for enzyme function. In both prokaryotic and eukaryotic systems, special transport systems exist in the cell envelope to pull the metals in ionic form through the cell membrane into the cell interior. Some of these transport systems are relatively non-specific and may transport several different ions. The affinity for different ions likely differs, however. Different ion species transported by the same transport system will compete with each other for translocation, depending on their respective concentrations. Both cationic and anionic species may be transported although by different carriers. In some cases, energy has to be expended by a cell to transport a metal into its cytoplasm. Because some of the transport systems are relatively non-specific, they may carry toxic ions into the cell (Jasper and Silver, 1977; Silver and Jasper, 1977). In the case of iron, special transport mechanisms exist in prokaryotes and eukaryotes to take up ferric iron chelated by appropriate siderophores (Lankford, 1973). The iron is released from siderophores by reduction after it has passed through the plasma membrane in chelated form (Lankford, 1973). In some cases, the siderophore has to be hydrolytically cleaved before the iron is reduced and released (Lankford, 1973).

Although transport systems which are driven through consumption of metabolic energy may cause intracellular accumulation against a concentration gradient over several orders of magnitude, the quantities of corresponding metal ions involved per cell are relatively small.

III. History of Biohydrometallurgy

The concept of using microbes as metal extractors of ores dates back to the early 1950's. In 1954, Bryner et al. published a paper in which they described experiments in which acidophilic thiobacilli from mine drainage of Kennecott's Bingham Canyon open pit mine were made to oxidize iron pyrites and copper sulfides including covellite, chalcopyrite, bornite, and tetrahedrite. The organisms were identified as Thiobacillus ferrooxidans and Thiobacillus Thiooxidans by Bryner and Jameson in 1958, the same organism shown earlier by Colmer and Hinkle (1947), Colmer et al. (1950), and Colmer and Temple (1951) to be the chief cause of acid mine drainage from bituminous coal mines. Thiobacillus ferrooxidans was shown to oxidize free sulfur, ferrous iron, iron pyrites, molybdenite, and several copper sulfide minerals. Thiobacillus Thiooxidans was shown to oxidize free sulfur but not sulfide minerals. These observations led in 1958 to the issuance of the first patent to Zimmerley et al., assignors to Kennecott Copper Corporation, on a cyclic leaching process employing acidophilic iron-oxidizing bacteria. This patent covered the leaching of metals from metal sulfide- and oxide- ores with the acidic ferric sulfate lixiviant generated by "motile, non-sporeforming, iron-oxidizing, autotrophic, rod bacteria which are tolerant to the metallic constituent or constituents to be extracted." In the process, the role of the bacteria was described as generating ferric sulfate and sulfuric acid from dissolved ferrous iron. Ferric sulfate was seen as the agent directly responsible for solubilizing the metal sulfide.

It was, however, subsequently shown that the bacteria could also oxidize the metal sulfides by direct attack (Silverman and Ehrlich 1964). It was also subsequently shown that other acidophilic iron- and sulfur oxidizing bacteria, some thermophilic, may participate in the leaching process (Brierley and Lockwood, 1977).

The early work of Bryner and co-workers (Bryner et al, 1954; Bryner and Anderson, 1957; Bryner and Jameson, 1958) showed that it was possible to leach metal sulfide ores microbially and led to leaching studies of a variety of other metal sulfides and to the development of methods for microbial leaching of ore concentrates (Silverman and Ehrlich, 1964; C.L. Brierley, 1978; Torma, 1978; Murr, Torma, and Brierley, 1978; Cripps 1980).

The observation that acidophilic iron bacteria can promote ore extractions led others to investigate the ability of neutrophilic, heterotrophic bacteria and fungi to promote ore extraction. Among the first to examine this approach were Perkins and Novielli (1962), who examined manganese extraction

from manganese ores; Pares (1964), who examined extraction of copper, iron, and gold from laterite and clay; Lyalikova and Mokeicheva (1969), who examined extraction of gold from gold ore; Wenberg et al.(1971) who examined the extraction of copper from carbonate rich copper ores; and Silverman and Munoz (1971) who examined titanium extraction from some igneous rocks.

The idea of using microorganisms to concentrate metals can be traced back to the middle 1960's when Walter Ezekial reported that the U.S. Bureau of Mines was investigating the use of bacteria to concentrate hafnium and zirconium from solution (Science News, 1966). The idea was based on observations that bacteria and other microorganisms can accumulate metals by concentrating them many fold over their concentration in the environment (Somers, 1963; Engel and Owen, 1970). The various mechanisms by which such accumulations occur began to be understood only more recently (Norris and Kelly, 1977; Brierley and Brierley 1983). Practical applications had begun to be suggested in the 1960's (Friedman and Dugan, 1968) and processes developed by the 1980's (Brierley et al.,1986).

IV. Case Studies of Biotechnology in the Minerals Industry

A. Biosorption

Introduction

Since early man discovered the special properties of metals that made them particularly appropriate for shaping into primitive tools and other beneficial uses, metals have held a noble position among the materials utilized by man in human civilization. Metals continue to be among the primary raw materials of an industrial society and economy up to the present . As long as metals continue to retain this distinctive role in industrial society, the mining, milling, and otherwise processing of these metals will result in the disposal of significant amounts as a waste product of these processes. As these metals often represent a threat to higher forms of life, they will likely remain an environmental problem that must be mitigated.

Although in the past these waste metals have been ignored or largely viewed as a nuisance by the industry, the possibility exists that these waste metals may prove to be a valuable resource. This scenario is only possible if the value of these metals exceeds the costs of removing and recovering them. Otherwise, they will remain a waste product whose impact on the environment must be mitigated. If and when such processes are developed, such waste streams may be viewed as a "minable" resource, similar to a naturally occurring ore body.

Biological metal recovery has often been mentioned as the process with the potential of reducing the costs of metal recovery from these waste streams sufficiently to be able to treat these waste metals as a resource. The general economic characteristics of biological processes, namely, low capital costs and the potential of very low or negligible operating costs, are ideally suited to such an application. At the same time, the primary economic drawback to biological processes, the reaction times, is not relevant to biosorption processes where the rate limiting parameter is not the metabolism of the cell but rather the ability to make physical contact between the cell envelope and the metals in the solution.

Only one biological metal recovery process has been made commercially available at present. That one process was developed and patented by Advanced Mineral Technologies Inc. (AMT) of Golden, Colorado. This process, termed the AMT-BIOCLAIM process, essentially utilizes dead biomass to perform this biosorption process. This section of this study will

compare the costs of this AMT process with conventional processes to remove and recover heavy and strategic metals from aqueous solutions.

The core of the AMT-BIOCLAIM process is an organic-based granule, the company prefers to call MRA (metal recovery agent). This granule is essentially a hard, granular biomass derived from select microbial biomass. Although the AMT process is proprietary, Polikarpov (1966), pointed out as early as 1966 that radionuclides present in an aquatic environment are accumulated by marine micro-organisms through direct adsorption from the water. He also pointed out that this property is independent of the life functions of the microbial cells since dead cells exhibited this property as well as or better than live ones. Since then, several scientists, particularly Beveridge (1981), have demonstrated the ability of various micro-organisms to biosorb a number of different metals including copper, cadmium, uranium, thorium, and gold.

The MRA granules developed by AMT are the insoluble solid biomass product derived chemically from the micro-organism, Bacillus subtilis. The metal adsorption capacity of this micro-organism is improved by treating the micro-organism with a caustic solution which converts it into a "solid" biomass (U.S. Patent #4,690,894, September 1, 1987). In addition to enhancing the metal sorbing properties of the biomass, the utilization of dead versus living organisms has further advantages. First, living organisms must be cultured which often is capital intensive and the culture is subject to potential contamination by other organisms. Second, these living organisms, as so often cited in the literature, have limitations on their ability to live and grow in high metal concentrations or extremes in pH and in the presence of other toxic components of a waste stream. Consequently, AMT's use of dead biomass (MRA granules) utilizes the organisms' enhanced ability to sorb metals without the limitations of maintaining the culture and growth of the living cells.

The MRA exists as a small (approximately 0.1mm) granular material with a density slightly greater than water. The technology employed in forming the MRA granules distributes metal-binding sites not only on the surface of the MRA granule, but throughout the granule itself. This dramatically increases the area of metal adsorption. The AMT-BIOCLAIM MRA granules can be used for recovery of precious metals from jewelry and plating manufacturer's wastewaters. The MRA can accumulate these metals even when they are complexed with cyanide.

These MRA granules provide direct accumulation of metals

from wastewater streams, eliminating the costly and cumbersome chemical pre-treatment. Sludge, the unavoidable by-product of chemical pre-treatment is not produced by the AMT-BIOCLAIM process.

AMT has produced two grades of MRA: (1) cationic MRA and (2) oxy-anionic MRA. Cationic MRA accumulates toxic cationic metal ions such as chromium, lead, silver, cadmium, zinc, copper, mercury, and nickel. Oxy-anionic MRA accumulates toxic oxy-anions of metal and metalloid complexes such as chromate, arsenates, and selenates.

A significant characteristic of MRA is its ability to be repeatedly regenerated. Regeneration of loaded MRA is accomplished through a two-step process. In the first step, the loaded metals are stripped from the MRA by the application of one of three chemical solutions: an acid, a caustic, or a proprietary neutral solution. In the second step, granules are washed and re-activated. Regeneration of MRA takes place in a separate container from the one in which active metal uptake is occurring.

Metals which have been stripped from the loaded MRA are concentrated in solution and may be: (1) recycled and reused by the producer, (2) recovered from the solution by an electro-winning process to yield a cathodic metal, or (3) added back into the process for pre-treatment by a precipitation technology that may be in place.

Advantages and Features of Biosorption Processes (Brierley et al., 1986)

The biosorption process developed by AMT has several advantages over competitive metal laden wastewater technologies. Following is a brief summary of some of these features and advantages.

Non-selectivity

MRA is not selective in the metals it accumulates; rather, it simultaneously removes several different hazardous metals from solution regardless of their differing concentrations. This makes MRA superior to metal-specific sorptive agents which can only remove one specific metal from solution. In addition, MRA removes only those metals which are considered hazardous, and allows non-toxic alkaline earth metals (calcium, sodium, potassium, and magnesium) to pass, reserving all possible sorptive sites for hazardous metals and

increasing metal loading capacity.

No concentration dependence

MRA loads single or mixed metals independent of influent concentration; therefore, it functions as effectively in wastewaters containing concentrated (100's of ppm) metals as it does relatively dilute (less than 10 ppm) streams. This property is an especially valuable one in industrial applications which produce a wastewater stream that continually changes in its metal concentration.

High efficiency

MRA has a high metal loading capacity; in many cases MRA loads single or mixed metals to greater than 10% of its weight. It has a metal removal efficiency of greater than 99%, yielding effluent with total metal concentrations in the ppb range, which is usually drinking water standard.

High versatility

MRA functions under a wide-range of pH (4-9) as well as temperatures (40-200° F) with no change in efficiency. The equipment is easy to operate outdoors, and may be used in industrial or remedial action applications. In the latter case, the ability to process lagoon or ground water without pre-treatment lends the MRA to extreme ease of operation in mobile treatment units.

Resistance to suspended solids and organic contaminants

MRA is not affected by low-level (less than 5000 ppm) organic contamination. Although MRA does not treat or significantly accumulate the organic fraction, it can be used in conjunction with other technologies to detoxify mixed contaminant flows. The physical properties of MRA make it possible for it to be utilized in a fluidized-bed system. This system allows particulate matter to pass through the MRA, and thus prevent fouling.

Regeneration

After it has been fully loaded with metals, MRA can be regenerated and then re-used. This eliminates the need for constant replenishment of MRA and also reduces its costs considerably.

The following table summarizes the performance characteristics of heavy metal wastewater treatment technologies (Brierley et al., 1986).

TECHNOLOGY	ABILITY OF SYSTEM TO RESPOND TO VARIATIONS IN:							EFF. IONS	CONC.
	FLOW	METAL CONC.	PH ION	SUSPENDED	OTHER SOLIDS	OTHER CONTAM	EXP METAL (OILS)		
HYDROXIDE PRECIPITATION	OK	NO	NO	OK	OK	OK	2-5		
SULFIDE PRECIPITATION	OK	NO	NO	OK	OK	OK	2-5		
ION EXCHANGE	NO	OK	SOME	NO	NO	SOME	<1		
REVERSE OSMOSIS	NO	OK	SOME	NO	NO	SOME	<1-5		
ION TRANSFER	NO	OK	SOME	NO	NO	SOME	<1		
EVAPORATION	NO	OK	OK	OK	SOME	OK	1-5		
ELECTRODIALYSIS	OK	OK	SOME	NO	NO	SOME	5-25		
AMT-BIOCLAIM	NO	OK	OK	OK	OK	OK	<1		

¹ ALL FIGURES IN mg/l

Process economics

The process economics of the biosorption system developed by AMT, as with any wastewater clean-up technology, is site specific. Costs will vary as certain parameters such as metal concentration and flow rates vary, not to speak of variations in the toxic elements present in the solution (AMT claims that their system is effective in removing any metal from solution with an atomic weight greater than that of aluminum). For this reason, it is particularly difficult to compare the economics of differing system without holding some variables constant. In this section, two scenarios are used to compared the comparative costs. The first, a primary effluent clean-up system and the second, a secondary or "polishing" system. In both analyses, the costs of the AMT biosorption system are juxtaposed with those of the best and most widely used alternative technology, caustic precipitation for primary treatment and ion exchange for polishing. The flow rates are held constant at 50,000 gallons per 24 hour day

The analysis then progresses to the examination of the comparative economics of these same technologies assuming metal recovery in both the primary and secondary treatment.

As mentioned above, the recovery of metals from these wastewaters has the potential to subsidize the mitigation of this environmental threat. A discounted cash flow analysis will be performed to examine the degree that such might be true. As caustic precipitation is not able to recover metals, the economics of removing the metals are compared with the AMT biosorption system with metal recovery in the primary treatment process. This analysis is conducted on the wastewaters of a hypothetical electroplating operation whose wastewater contains the metals nickel, cadmium, chromium, and zinc. Finally, the costs of treating large, dilute aqueous solutions of metals typical of the precious metal mining and milling operations will be briefly examined.

Primary treatment

Primary treatment of metal-contaminated wastewaters is defined as that treatment technology or system which is used to remove the bulk of the metals present in a waste stream. For purposes of determining the economics, waste streams containing 60 milligrams per liter (mg/l) or more of metals are considered to be streams for primary treatment.

In primary treatment, the prevalent technology for removal of metals is chemical precipitation using caustic, an alkali such as sodium hydroxide, lime or limestone. This process is typical among the electroplating industry where approximately 75% of all electroplating operations treat their aqueous metal bearing waste in this manner (Grosse, 1986). Of these, the bulk utilize lime to raise the ph of their wastewaters sufficiently for the metals to precipitate out. The level of ph necessary is a function of the metal ions present in the solution, therefore the treatment of mixed-metal aqueous wastes requires some adjustment of ph to precipitate out each metal. The metal hydroxide precipitate forms a floc which is then removed from the water by gravity settling or filtration. This floc or sludge, which can be defined as a hazardous waste, may require fixation or encapsulation to ensure post-disposal non-leachability. Key economic components of this precipitation technology are the costs of dewatering, handling and final disposal of the sludge in a hazardous waste landfill.

For comparison purposes, the following conditions are assumed:

- (1) flow volume is equal to 50,000 gallons per day (24 hour day), 5 days a week
- (2) metal concentration is equal to 60 mg/l

- (3) capital equipment price for AMT-BIOCLAIM process includes metal removal, MRA regeneration, and metal recovery system
- (4) the expected life of the equipment (depreciation period) for both processes is 5 years
- (5) operating costs for AMT-BIOCLAIM include MRA, chemicals for MRA regeneration, and labor
- (6) operating costs for caustic precipitation include chemicals and labor
- (7) metal loading on the MRA is 10% of weight
- (8) the MRA is recycled 25 times in the amt process
- (9) sludge disposal costs are estimated at \$75 per drum for chemical precipitation

It should be noted here that the costs of disposing of the hydroxide sludge generated by the chemical precipitation process will vary by location. Costs of disposal in California are the highest. The figure of \$75 per drum is an average figure from across the U.S.

COMPARATIVE ECONOMICS OF PRIMARY TREATMENT PROCESSES

COST	AMT BIOCLAIM	CHEMICAL PRECIPITATION
CAPITAL COST	69,040	328,000
METAL REMOVAL	50,000	N/A
REGEN & RECL.		
TOTAL CAPITAL COST	119,040	328,000
OPERATING COSTS (DAILY)		
CHEM/MRA/LABOR	270	350
SLUDGE DISPOSAL	N/A	400
REGEN/RECL/LABOR	97	N/A
TOTAL OPERATING COSTS	367	750
TOTAL COST PER GALLON (INCLUDING DEPREC. EXPENSE)	\$0.0090	\$0.0200

This comparison of the economics of the chemical precipitation with the AMT biosorption wastewater treatment process clearly indicates that in the aforementioned application, biosorption can reduce the cost per gallon of treated wastewater by over 50%. It is important to note that the number of times the MRA can be regenerated is a key assumption in this economic analysis. The greater the number of times the MRA can be regenerated, the lower the treatment costs.

Other important factors to consider in this comparison include:

- (1) this analysis does not include the potential liability costs either in insurance costs or possible law suits that may result from the perpetual liability from the generation and disposal of the hazardous hydroxide sludge generated by the chemical precipitation process. If these costs had been included, the biosorption process economics would appear to have an even greater cost advantage.
- (2) the biosorption process produces a cathode metal that can be recovered and returned to commerce and potentially providing the waste processor a cost subsidy.
- (3) Most caustic precipitation systems under normal operating conditions are unable to achieve effluent standards and secondary treatment, or polishing, is required for the generator to comply with effluent standards. The biosorption process achieves discharge standards without additional processing or polishing.

Although the economics of the biosorption process are favorable under the metal concentrations outlined in this example, the costs of regenerating the MRA limit the use of the technology to more concentrated metal solutions. As the metal concentrations rise above 100mg/l, so do operating costs. Above 250mg/l, apparently the cost advantage of the AMT-BIOCLAIM process is dissipated by the higher costs of MRA inventory (C.L. Brierley, 1988).

Secondary treatment

Secondary treatment or polishing, of metal contaminated wastewaters is defined as that treatment technology or system

which is used to remove residual metals that are present in the effluent after primary treatment. Polishing is often required for waste effluents to achieve strict discharge standards. For purpose of this economic comparison, effluents requiring polishing have less than 60mg/l of total metal present.

Ion exchange technology is the best alternative process in the polishing of metals from wastewater streams. Ion exchange is a separation technology which removes various ionic species from solution via interchanging reversible ions between the solution (aqueous waste) and the resin.

For the following economic analysis , the following assumptions will be made:

- (1) flow volume is equal to 50,000 gallons per day (24 hours) 5 days per week
- (2) total metal concentration is 10mg/l
- (3) capital equipment costs for the AMT process include contactor and initial fill of MRA.
- (4) Capital equipment costs of the ion exchange system include contactor, prefiltration, and initial fill of resin
- (5) equipment is depreciated over 5 years for both systems
- (6) operating costs include MRA, labor, and regeneration for the biosorption process
- (7) operating costs include ion exchange resin, labor, and regeneration for ion exchange system
- (8) both systems are polishing effluent that has passed through a caustic precipitation system

COMPARATIVE ECONOMICS OF SECONDARY TREATMENT SYSTEMS

COST	AMT BIOCLAIM	ION EXCHANGE
CAPITAL COST	\$78,260	\$98,000
OPERATING COST	\$65	\$101
COST/GALLON TREATED	\$0.0025	\$0.0035

It is apparent that the biosorption secondary wastewater treatment process is significantly less expensive than ion exchange treatment under the aforementioned conditions. The biosorption process is able to reduce capital costs by 20%, operating costs by 36%, and total treatment costs per gallon by 28% from that of the ion exchange system.

Discounted Cash Flow (DCF) analysis

Discounted cash flow (DCF) analysis is a means of determining the value of the cash flows of a capital project over the operational life on a present value basis. In other words, all cash flows are summed and discounted by the time value of money to the firm after adjustments for inflation and taxes. We have developed such a DCF model for the two processes above with the following assumptions:

- (1) all assumptions listed above remain in place
- (2) the cost of capital is 15%
- (3) operating costs increase by the general rate of inflation in the economy, in this case 6%
- (4) all tax laws, rates and depreciation schedules extant in the U.S. in 1988 are applied
- (5) the marginal tax rate is 34%
- (6) operational life is 10 years

The following are the results of this analysis for these two processes and examples:

Comparative Discounted Cash Flow Analysis

	AMT Bioclaim	Alternative Process
Primary treatment	(\$787,460)	(\$1,682,360)
Secondary treatment	(\$177,446)	(\$ 260,736)

The discounted cash flow analysis provides us with a better picture of the relative costs and therefore value of the competitive processes. In the primary treatment of metal-laden wastewater, the biosorption process is less than half the cost over ten years than chemical precipitation. Remember that this analysis assumes that the precipitate disposal costs--an operating cost-- would only rise by the general inflation rate and potential liability costs are not included. Disposal costs that increase by faster than the general rate of inflation and some contingency for potential liability (insurance or contingency fund reserve) would favor the biosorption process to an even greater extent.

As for the secondary or polishing systems, the discounted cash flow analysis once again shows considerable cost savings for the biosorption process over the ion exchange system. Savings are over 30% relative to the ion exchange process.

Please note that these costs and comparisons are only valid under the circumstances outlined above and cannot necessarily be extrapolated to a third environment.

Accumulating strategic metals

The following is a hypothetical case in order to compare the costs of the biosorption process to caustic precipitation in a primary treatment process. In this case though, the metal reclamation properties of the biosorption process will be utilized to determine the potential cost offsets of recovering the waste metals rather than disposing of them as with chemical precipitation or some other alternative primary wastewater treatment systems. The EPA studies indicate that a large part of the operational costs of treating metal bearing wastewater could be subsidized by the sale of the recovered metals. The EPA estimates that the annual metal values lost in the waste streams of U.S. electroplating

industry alone at \$58 million in 1985 (EPA, 1986).

Our case study is an electroplating company that produces approximately 50,000 gallons of wastewater daily. This wastewater contains zinc, cadmium, chromium, and nickel in the following amounts, 40 mg/l, 20 mg/l, 18 mg/l, 12mg/l, respectively. This analysis makes the same assumptions as the previous DCF analyses above except that 98% of the metals are successfully recovered and the recovered metals are valued at the following prices (Metals Week, 1988):

zinc	\$ 0.60/lb
Cadmium	1.50/lb
Chromium	3.50/lb
Nickel	.60/lb

The following is the adjusted discounted cash flow analysis of the biosorption process with the recovery and recycling the metals from the waste stream versus chemical precipitation without any recovered metal value.

DISCOUNTED CASH FLOW ANALYSIS	
PROCESS	DISCOUNTED CASH FLOW
AMT-BIOCLAIM	\$ 742,194
CHEMICAL PRECIPITATION	(1,682,360)

This analysis provides clear evidence that the utilization of a process that recovers metals from a wastestream such as biosorption, makes a significant difference in the overall economics of de-toxifying the process waters. In fact, in this case of primary treatment, the discounted value of the recovered metals exceeds the discounted costs of de-toxifying the wastestream with the biosorption process over ten years of operation. This provides the waste processor with a net positive cash flow of \$742,194. For the chemical precipitation process, a net negative cash flow of \$1,682,360 is realized over the ten years of operation.

As mentioned above, it was assumed that the process recovered 98% of the metals in solution and no costs were associated with the electrowinning of the metals. Sensitivity

analysis indicated that the cash flows would remain net positive for the term of the project until the value of the recovered metals dropped below 51% of the recovered values assumed above. In other words, the process would pay for itself until the costs of electrowinning, a decline in metal prices, a decline in metal recoveries or a decline in metal concentrations reduced the recovered value of the metals to 51% of that level assumed to be available in this solution.

This same type of analysis has been conducted for the secondary treatment processes. Similar results were obtained but with one exception, the net cash flows do not turn positive for either the biosorption or ion exchange process. This is primarily due to low concentrations and therefore low metal values per gallon treated, indigenous to secondary treatment. These results have been summarized below:

PROCESS	DISCOUNTED CASH FLOW
AMT-BIOCLAIM	(\$23,535)
ION EXCHANGE	(\$106,826)

This analysis make the same assumptions as in the above analysis except that metal concentrations are exactly 10% of those above with a total metal concentration of 10mg/l.

Larger, more dilute wastewater systems

In personal communication with Corale Brierley, vice-president and one of the founders of Advanced Mineral Technologies, she indicated the AMT biosorption process has considerable economies of scale. For applications typical in some mining, smelting, or refining operations, operating costs on a per gallon basis would be considerably lower than those outlined above. For example:

- (1) in an operation with a wastewater stream of 2,000,000 gallons per day and about 10mg/l of metals, operating costs would fall to just \$0.0013 per gallon. This application would utilize a dispersed bed reactor, which has very low capital cost and requires a minimal amount of MRA inventory.

- (2) In an operation with a wastewater stream of 12,000,000 gallons per day and about 5mg/l of metals, operating costs would fall to \$0.00037 per gallon of treated effluent. This system would also employ a dispersed bed reactor to minimize capital and MRA costs.

Biosorption Conclusion

Anticipation that a biological mineral technology could reduce costs of recovering metals from the aqueous process effluent has been realized. The AMT biosorption process has significantly reduced metal recovery costs to the point that in some process waters containing high levels of relatively valuable metals, the costs of removing the metals may be exceeded by the value of the recovered metals.

Furthermore, the AMT biosorption process has proven to be a low cost metal removal system even when the metals are not reclaimed in both secondary and primary waste water treatment. It appears as though in high volume, dilute solutions typical of the mining, milling, and smelting operations the process economics are further enhanced. On the other hand, due to the nature of the process and the regeneration of the MRA, in very high concentrations of metals, the process loses its cost advantage over competitive processes when the metals are not recovered.

This area of research, biosorption of metals, is a very active one in the field of biological mineral technologies. Consequently, although the AMT biosorption process presently is the only commercially available biological metal recovery system, it is reasonable to anticipate that further research and development will lead to additional processes with enhanced effectiveness and cost advantages in the coming years. This, in turn, could lead to the development of an industry that not only processes waste waters, but "mines" them for their metal and other mineral values. The end result could be not only less expensive wastewater processing, but significant profits for some enlightened entrepreneurs and their financiers. Finally, such processes are likely to reduce the industrial world's demand for metals (*ceteris paribus*), as metal processes will become more efficient and less wasteful.

B. Copper Bioleaching Case Study

Introduction

Far and away, the utilization of biological techniques have advanced furthest in copper recovery than in any other area. It is estimated that in 1988, U.S. production of copper by biological leaching will exceed 250,000 tons with a dollar value in excess of \$650,000,000, setting a record for single year production of copper from biological means (Holmes et al., 1988). The reasons for this growth of biological leaching of copper are primarily economic. Dump leaching at Morenci and Burro Mountain Mines are estimated at \$.30/Pound, about 50% less than conventional copper recovery techniques (Engineering Mining Journal, 1990).

Copper leaching began almost by accident, as snow and rain percolated through the dumps it was found that the run-off contained a substantial amount of solubilized copper. This method was first commercially utilized at the Rio Tinto Mine as early as 1752 and the first recorded utilization in North America began in 1907. Initially, the process was little understood, but since Colmer and colleagues (1950) first identified the microorganism Thiobacillus ferrooxidans in 1950, our understanding, utilization and optimization of this process has expanded rapidly. Now, copper producers worldwide have found that the thiobacillus ferro-oxidans organisms can assist them in producing copper much less expensively than conventional means.

This segment of the economics study will examine the costs of producing copper from dumps, heaps, and in-situ leaching operations utilizing Thiobacillus. Copper leaching is a very site specific operation, as with most mineral production techniques, so cost figures contained within will attempt to cover the industry rather than any single operation.

Dump leaching

Leaching and recovering copper from as-mined materials is fairly common practice at open-pit porphyry copper operations in the U.S. As noted above, such operations began shortly after the advent of open-pit operations early in this century. Initially, leach production began accidentally as the overburden from low-grade mines seemed to leach naturally. As rain and snow provided the necessary water, the pyrite oxidized to provide sulfuric acid and ferrous iron in solution. The acid leached the non-sulfide copper minerals and maintained a solution ph low enough to prevent copper and iron hydrolysis. Bacteria present in the dumps promoted conversion of ferrous iron to the ferric state so that sulfide copper was

also leached. The result was small flows with high concentrations of copper that flowed from the toes of the dump. The copper in solution was easily recovered by diverting the streams through piles of scrap iron.

Dump and Heap Leaching Economics

Although this field of biohydrometallurgy has been the most successful in terms of the number of operations utilizing and dollar volume of production, very little data exists on industry wide data on production. It must be noted, however, that the fact that so many operations utilize dump leaching would seem to testify to the favorable economics of such a operation. Estimates within the industry range as low as total production costs \$.30/pound for large operations in Arizona utilizing solvent extraction (Engineering Mining Journal, 1990). The breakdown of these costs are largely unavailable and considered to be proprietary information by the individual operations.

W.J. Schlitt (1980), of Kennecott Copper, estimated in 1980 the following costs for dump leaching of copper. First, Schlitt points out that at most dump leaching operations, the leaching operations do not bear the costs of mine development and comminution, as the waste heaps had to be moved in order to provide access to the higher grade ore. Schlitt estimates that when cementation is utilized as a copper recovery process, the cost of iron scrap probably accounts for over 50% of direct operating costs. Another 25% is estimated to be attributed to the costs of pumping the large volume of low grade solution. He estimates that typical dump leach production costs in precipitate probably range from \$25 to \$.45 (1980 dollars), which agrees with anecdotal information from various industry sources. Further processing then involves smelting and electrorefining. He estimates that refining would add \$.10 To \$20 per pound to total production costs.

In recent years a majority of the large copper leaching operations have converted their copper extraction process from the common cementation process to solvent extraction. The motivation for this change has been primarily economic with reported cost savings exceeding 50% in some operations. It must be noted though that solvent extraction is a capital intensive process relative to cementation and therefore has significant economies of scale. For some smaller leaching operations these economies may never be adequately realized to reduce costs significantly to warrant a change to solvent extraction .

Concentrate leaching economics

The successful leaching of copper concentrates bacterially, is an idea that has bounced around the biohydrometallurgical field for over two decades. This technique would supposedly take advantage of the low capital and production costs of bioleaching and combine them with the favorable economics of treating only copper concentrates.

The first estimated cost estimates as such a process appeared in 1978 when Mc Elroy and Bruynesteyn (1978) published the results of their demonstration process for a continuous plant for treating chalcopyrite concentrates at B.C. Research. The process reportedly able to produce electrowinning grade leach solutions in 50 hours. Despite the apparent success of such a process in the intervening decade, no such plant has been built to process copper concentrates. It is suspected that this is the case for several reasons: first, due to the downturn in copper prices that occurred soon after the publication of these results, little capital investment was made in new capital equipment by the copper mining industry in North America: second, the authors estimates do not take into account the time value of money. In other words, although the data that follows seems to indicate that such a process is economical, if one takes into account the cost of capital while waiting for the full recovery of metal values from the concentrate, it significantly increases the cost.

The following estimates were developed by Dravo Corporation for the authors in 1973 for a plant to treat 200/tons/day of chalcopyrite concentrate. The capital cost estimate included engineering, procurement, management, construction, and profit, but did exclude the cost of the site, insurance and taxes.

MC ELROY AND BRUYNESTEYN CAPITAL COST ESTIMATE FOR CONCENTRATE LEACHING

	1973 \$	1987 \$
LEACH PLANT	9,400,000	24,030,000
ELECTROWINNING PLANT	4,200,000	10,740,000
TOTAL	13,600,000	34,770,000

THE OPERATING COST ESTIMATES ARE BELOW

		1973 \$	1987\$
LABOR	2.09	5.34	
POWER	2.06	5.27	
MAINTENANCE (5% OF CAPITAL)	2.02	5.16	
LIMESTONE	.75	1.92	
FLOCCULENTS	.21	.54	
NUTRIENTS	.12	.31	
GRINDING BALLS	.06	.15	
	<u>7.31</u>	<u>18.69</u>	
TOTAL			

More recent work by Lawrence, Vizsoli, Vos, and Bruynesteyn (1984) unveiled a process to continuously bioleach copper concentrates using a silver catalyst. This process was also developed for chalcopyrite. This process achieved enhanced copper leach rates and extractions while also converting sulfide sulfur to elemental sulfur. The authors reported that "high recovery of silver from the flotation tails is essential for process viability". Unfortunately, at last report the authors were unable to achieve a high recovery of silver from the tails and consequently the process was judged uneconomic.

In-situ leaching

In-situ leaching of low grade copper ore has long been speculated to be an extremely appropriate and profitable application of biological leaching. In situ leaching would seem particularly attractive since the operations from mining to flotation use 50% of the total energy and involve approximately two-thirds of the total capital cost required to produce copper (U.S. Bureau of Mines, 1985). As detailed above, dump leaching has proven profitable for almost eight decades in North America, but the costs of developing the mine and moving the ore are often not attributed to the leaching operation. With in-situ leaching, the leach operation must justify all costs to prove viable and we will examine several of these operations.

The viability of in-situ leaching is largely a factor of the

mine development and comminution costs. If these costs can be reduced to reasonable levels, the leaching operation is often satisfactory.

Ore bodies that are too low grade or too small to be mined by conventional methods have potential for in-situ methods. The relatively low capital costs and production costs make some of these previously regarded uneconomical deposits, economic with the utilization of in-situ leaching. In-situ is not normally considered for other types of deposits due to the slow recovery of leaching (5-15 years for 60%). Also, the leaching of old mine workings such as block caves, backfilled stopes, and open pits, is often an economic method for recovering additional copper when conventional minable reserves have been depleted.

Copper bearing deposits vary considerably, so the methods and economics will vary likewise. Regardless of the preparation method, in situ leaching must meet the following requirements to be successful (Ahlness, 1984):

- (1) the host rock must not be acid consuming (excessive H_2SO_4 consumption)
- (2) the host rock must not decrepitate to seal intrarock fractures and block solution flow
- (3) the rock must be sufficiently fractured to permit access of solution to copper minerals
- (4) copper minerals must be concentrated along the fractured planes of rock
- (5) there must be a solid or impervious surface under or surrounding the deposit for liquor collection
- (6) the copper minerals must dissolve quickly enough to provide adequate cash flow to meet capital costs
- (7) it must have the ability to recirculate the solution through the ore several times without excessive loss or contamination
- (8) an adequate supply of water must be available at reasonable costs

In situ leaching economics

As mentioned above, due to the tremendous differences in the

mineralogical composition and size of the ore, it is difficult to estimate the costs of production. Generally, before making a determination to leach with in-situ techniques, the mine operator performs a pilot scale operation on a segment of the ore body to estimate costs for the entire body.

Cooper (1967) estimated the costs of in-situ leaching in Arizona for the production of 9000 short tons of copper equivalent per annum. This data for a copper cementation recovery of 70-80% copper, are translated below into current dollar values.

COSTS OF IN-SITU LEACHING OF COPPER ORE IN ARIZONA

ITEM	\$/POUND COPPER IN 1987 \$
LABOR	.0316
ACID	.1105
IRON	.1142
PUMPS AND PIPING	.0027
ELECTRICITY	.0095
MISCELLANEOUS	.0714
TOTAL	<u>.3399</u>

More recent data on the costs of in-situ leaching comes from a study done by Ismay, Rosato, and Mckinnon (1986) of the Noranda Research Center. This study was for a 1000 ton/year recovery operation from a .9% copper deposit at the Geco mine in Manitouwagdge, Ontario, roughly 1000 meters beneath the surface. The mineralogy of the deposit consisted of disseminated sulfides in sercrite schist with no appreciable precious metal content. The site had already been mined and abandoned so access to the mine was already available. The feasibility study was conducted using cementation as a recovery process due to the fact that production tonnage was expected to be smaller than 2000 tons per year. These costs are summarized below:

COST ESTIMATE FOR IN-SITU LEACHING BY ISMAY

COST COMPONENT	CEMENTATION	S/X-EW
LABOR	4.51	4.51
REAGENTS	4.82	3.41
SUPPLIES	.55	.55
POWER	16.70	16.70
RESIDUE DISPOSAL	1.30	1.30
	<u>27.88</u>	<u>26.77</u>

The various costs for the recovery section are summarized below:

OPERATING COSTS FOR RECOVERY SECTION

COMPONENT	CEMENT.	SX	EW	TOTAL SX-EW
LABOR	26.95	17.95	31.44	43.99
REAGENTS	44.99	11.48	1.69	13.17
SUPPLIES	6.18	2.20	3.98	6.18
POWER	1.50	1.63	9.17	10.80
	<u>79.62</u>	<u>33.26</u>	<u>46.28</u>	<u>79.54</u>
SUPERVISION	5.84			5.84
TOTAL	<u>85.4</u>			<u>85.40</u>

This study concluded that from a net present value perspective using a 15% cost of capital, that the NPV of such a project at Geco assuming a copper price of \$1.00/pound would be \$-22 million. They estimated that a reduction of operating costs of 87% or an increase in the price of copper to \$4.19 Per pound would be necessary to achieve a npv of 0. For comparison purposes, they estimated that for conventional mining at the same site, the npv would be \$-25 million. They point out though that under conventional mining conditions, the npv reaches 0 with a 45% reduction in operating costs or an increase in the price of copper to \$1.79. The authors conclude that neither in-situ leaching nor conventional leaching is economically feasible at the site, but that conventional mining is more sensitive to the parameters that affect copper production.

This research also did sensitivity analysis comparing in-situ leaching and conventional mining. They conclude that for very low grade ores, in-situ is superior to conventional but that conventional is much more sensitive to ore grade. They also conclude that faster leach rates would improve the economics of the project, but that the most important hindrance to the economics of bioleaching in-situ are the high mining development costs. They estimate that 66% of all costs correspond to mining development, while only 5% are attributable to leaching and 29% to recovery. While mining development costs are marginally lower for in-situ (\$14.74/T) than conventional mining (\$17.76/T), conventional mining relises 85% of the revenues from the contained copper in 3 months versus over several years for leaching and then only 55% of the copper value.

Copper Leaching conclusions

Biohydrometallurgy has made its greatest in-roads in the production of copper. Although the copper industry sometimes overlooks the microbiological nature of their leaching operations, the production of over 25% of all copper produced in the U.S., the world's second largest copper producer, is the result of the reactions carried out by the ubiquitous Thiobacillus ferrooxidans. It should also be noted that despite its unsung role, this bug is probably responsible for the financial solvency of several of the major copper producers during the period of overproduction and low prices from 1982-1986, as several companies shut down their high cost conventional production systems but continued to leach copper, most notably Kennecott's Bingham Canyon operation.

During this period of relative prosperity in the copper mining industry with prices at or exceeding the \$1 per pound mark,

we have seen several companies, most notably Phelps Dodge, expand their ability to produce leach copper. Due to this increased capacity, we expect copper biohydrometallurgy to expand to over 30% of total U.S. production by 1990.

Although successful in-situ leaching has been practiced in the U.S. at Magma Copper's Miami Mine for over 20 years, the industry has not given this technique its relative due primarily because of its slow copper recovery rate. As ore grades fall in coming years while energy, labor, and capital costs escalate, it is likely that the interest in in-situ leaching will be revived. This technique holds the promise of being the least cost method of copper and other base metal production at new and remote copper deposits. Although its recovery rates are considerably slower than conventional mining, the capital investment in such operations is very low. The primary impediment to increased in-situ production continues to be not the leaching process, but rather the costs of reducing the size of the ore to allow for adequate percolation and surface area contact. As better techniques are developed for ore comminution, the economics of in-situ copper mining by biological means will become so advantageous so as to likely make conventional techniques obsolete. In the past, such innovative comminution techniques such as detonating a nuclear device have been proposed (Engineering Mining Journal, 1967) the industry needs to apply such creative thinking to comminution techniques in the future. Blasting techniques have improved, but remain a relatively primitive technology for reducing the size of rock. The application of such new technologies as lasers and ultrasound deserve attention as well as others, in order to fracture ore bodies making them amenable to in-situ leaching. These techniques may prove to be more expensive than blasting but if in-situ techniques can be properly and effectively applied such additional costs will be warranted by significantly reduced overall production costs.

Concentrate leaching of copper ore has little potential to be a viable technique in reducing copper production costs. About 2/3 of the cost of producing copper are borne before the ore or concentrate even gets to the smelting/refining stage. Therefore, the leaching of concentrates, which at best are only marginally less expensive than other techniques is addressing only 1/3 of the total costs of production. If this concentrate leaching could reduce the costs of smelting/refining to 0 (an unlikely proposition) it could at best reduce the production costs of copper by 1/3. We have already seen where dump leaching has effectively, halved the costs of copper production and in-situ nearly so.

In summary, biohydrometallurgy's greatest potential is in copper extraction from natural vessels such as dumps, heaps,

or in-situ. Cost savings, once a concentrate has been produced, are marginal at best. Improved techniques of rock fracturing hold the key to additional expansion of in-situ copper mining, but further optimization of the process can have marginal improvements. Moreover, with additional research and development and greater scientific understanding of the responsible micro-organisms, the other limiting parameter, recovery rates may be able to be significantly shortened. Even further into the future, it may be possible to utilize the cellular products from the micro-organism in direct leaching of copper ore and significantly increase recovery rates and reduce recovery times.

C. Gold Bio-oxidation Case Study

Introduction

Many gold ores are refractory to conventional processing technologies and hence prove to be uneconomical to develop. The refractory nature of these materials can be the result of various components including; iron sulfide minerals, silica minerals, tellurides, organic compounds, and sulfosalts.

Gold locked within iron sulfide minerals account for a large number of these refractory gold ores. These minerals consist primarily of pyrite or arsenopyrite. These must be oxidized to free the encapsulated gold and allow it come into contact with cyanide to permit efficient leaching by cyanide.

Biological oxidation provides one more alternative to the mineral resource industry for freeing this encapsulated gold to improve gold recoveries and hence, economically develop these ore bodies. Biological oxidation of refractory gold ores brings the mining industry into contact with the biological sciences and adds bio-oxidation to the already large array of process alternatives including pressure oxidation and roasting. The mining industry is not yet comfortable with these biological processes, which has lead to skepticism and slower commercial adoption.

This unfamiliarity and discomfort with biological processes for mineral recovery is persistent, in spite of a long history of biological processes in mineral recovery. The first recorded application of biological mineral recovery was at the Rio Tinto copper mine in Spain about 1752. In the New World, copper dump leaching utilizing Thiobacillus ferrooxidans dates back at least to 1907.

The first research in the biological oxidation of refractory gold ores dates back to at least 1970 when the Department of Metallurgical Engineering at the University of British Columbia undertook this work. This research was under the leadership of Albert Bruynesteyn and Richard Lawrence. Further pioneering work has been done in the United Kingdom by A. Pinches and F. Pooley, as well as in the South Africa by Eric Livesey-Goldblatt. It appears that in the Soviet Union, the research efforts in bio-oxidation have been led by Dr. G.I. Karavaiko of the Academy of Sciences at Moscow.

From these 18 years of research have come at least three commercial plants utilizing bio-oxidization of refractory gold ores. The first was at Fairview Mine, Barberton, Transvaal South Africa that processes 10 tons/day and was commissioned in 1986. This project was based upon a design by the Gencor Group in Krugersdorp. This project has reportedly reduced the

reaction time in recent months to 3-4 days from the initial 10 days.

The second commercial scale bio-oxidation plant was installed in Zimbabwe at the Riverlea Mines at Kwekwe to treat 5 tpd concentrate, initially, with plans to expand to 15 tpd in the near future. This plant reportedly went on-line in 1987.

Finally, Snow Lake Gold has installed a biological oxidation plant to treat 3000-5000 tons per month of arsenical tailings at Snow Lake, Manitoba. The process design was based on test work by Malcolm Southwood and designed by Bob Smith of Golden Dumps Research, Benoni, South Africa.

Giant Bay Resources initiated a test plant in the spring and summer of 1987 to oxidize refractory gold ore at Giant Yellowknife's Salmita mine in the Northwest Territories, Canada. This successful test plant provided the data for Wright Engineers Ltd. of Vancouver, British Columbia to develop estimates comparing the economics of pressure oxidation, roasting and bio-oxidation as a means of pre-treating refractory gold ores before cyanidation.

Characteristics of Biological Oxidation of Refractory Gold Ore

Marchant and Lawrence in their 1986 study titled "Flowsheet design, process control and operating strategies in the biooxidation of refractory gold ores" (Marchant and Lawrence, 1986) compare the features of biooxidation with pressure oxidation and roasting.

COMPARISON OF SEVERE OXIDATIVE PRETREATMENT ALTERNATIVES

COST FACTOR	BIO	PRESS OX	ROAST
1. SELECTIVE SULPHIDE OXIDATION	YES	NO	NO
2. HISTORIC DATA AND DESIGN AVAILABLE	NO	YES	YES
3. AMENABLE TO LOW SULPHIDE CONCENTRATES	NO	YES	YES
4. CONVENTIONAL MINERAL PROCESSING EQUIP.	YES	NO	NO
5. SOPHISTICATED DESIGN	NO	YES	NO
6. SOPHISTICATED OPERATOR KNOWLEDGE	NO	YES	NO
7. HIGH LEVEL PROCESS CONTROL	NO	YES	NO
8. SPECIAL MATERIALS OF CONSTRUCTION	NO	YES	YES
9. HIGH MAINTENANCE/WEAR EQUIPMENT	NO	YES	YES
10. HIGH PRESSURE VESSELS, LINES, VALVES	NO	YES	NO
11. SOPHISTICATED OFF-GAS TREATMENT	NO	YES	YES
12. VESSEL HEATING/COOLING CONTROL NEEDED	YES	YES	NO
13. OXYGEN AND/OR STEAM PLANT REQUIRED	NO	YES	NO
14. AMENABLE TO ALKALINE AND/OR CARBONACEOUS	NO	YES	YES
15. OXIDE PRODUCT WASHING RECOMMENDED	YES	YES	YES
16. SALEABLE ACID CO-PRODUCT	NO	NO	YES
17. POSSIBLE DIFFICULTIES IN SILVER METALLURGY	NO	YES	YES
18. ARSENIC PRODUCT AS AS ₅	YES	YES	NO

Biological oxidation processes may be particularly attractive as a metallurgical process when selective oxidation of one sulfide mineral over another, or a preferred rate of oxidation can be exploited (see #1 above). For example, Thiobacillus ferrooxidans will, under certain conditions, oxidize arsenopyrite at a much higher rate than pyrite. As pointed out by Marchant, if the refractory gold ore is associated with arsenopyrite, then subsequent cyanidation of the washed bioleach residue can achieve excellent gold recovery improvements after oxidizing as little as 10-20% of the total sulfide in the feed. In this type of ore, the advantage of bio-oxidation is that the time necessary for bio-oxidation is dramatically reduced while oxidation can be carried out with higher pulp densities and the volume of acid that must be neutralized as well as ferric hydroxide-gypsum precipitates to be disposed of is sharply reduced.

Factors Limiting the Economics of Bio-oxidation of Gold Ore

- * Size and number of tanks required for adequate oxidation of sulfide.
This capital cost item is dependent upon:
 - (1) time required for degree of oxidation
 - (2) percent solids at which bio-oxidation can be carried out optimized in conjunction with residence time.
- * Energy required for agitation/aeration of pulp during bio-oxidation
- * Cooling costs for pulp which depends on
 - (1) temperature for optimum oxidation
 - (2) ambient climactic conditions
 - (3) volume of pulp/air/solution to be cooled
 - (4) energy costs
 - (5) the amount of sulfides in the ore/concentrate
- * Acid neutralization costs which are dependent upon:
 - (1) acid neutralization capacity of the concentrate and mill tailings
 - (2) cost of lime and/or limestone delivered to the site
- * Effluent/precipitate sludge disposal costs which depends upon local environmental laws

Applicability of Bio-oxidation of Refractory Gold Ore

Biological oxidation has been applied and proposed for the following types of applications:

- i. Bio-oxidation of refractory arsenopyrite gold bearing concentrates
- ii. Bio-oxidation of refractory concentrates consisting of pyrite and arsenopyrite in which the gold is encapsulated in the arsenopyrite grains
- iii. Heap leaching of refractory sulfide ores which would be bio-oxidized in heaps or dumps prior to neutralization or cyanidation.
- iv. Bio-oxidation of sulfides encapsulating gold in finely divided tailings in-situ
- v. Bio-oxidation of a refractory auriferous pyrite mixed with refractory silver-manganese ores

Of the process economics described below, the Giant Bay Process is application #1, while the processes described by Bruynsteyn and Marchant are application #2, and the processes described by Errington, et al. and Livesey-Goldblatt are

application #4.

Economics of gold bio-oxidation

The Giant Bay Resources pilot plant at Salmita, NWT

As reported above and in numerous periodicals, Giant Bay Resources undertook to test a proprietary biological oxidation process at Giant Yellowknife's Salmita mine in the Northwest Territories. This test plant was scaled up to operate at 10tpd on the run-of-the-mine ore from the Salmita mine. The following is an analysis of the ore treated at Salmita:

iron	2.78%
arsenic	.73%
total sulfur	.89%
gold	.667oz./t

Vancouver Petrographics Ltd. characterized the ore as follows:

"finely ground quartz-feldspathic material with 3-5% sulfides. Pyrrhotite is the dominant sulfide in all samples followed in abundance by magnetite, chalcopyrite, arseno-pyrite, and gold. Gold occurs namely as free, small, isolated grains."

The Giant Bay Resources test plant processed 400 tons of ore in a two-month period that ended in mid-July 1987. From this test plant, Wright Engineers Ltd., of Vancouver, British Columbia, was able to estimate the capital and operating costs of a commercial scale biological oxidation plant. The data from the cost estimate will serve as the foundation for this segment of this study.

Whatever the technical success of Giant Bay's test plant and process, the most important factor for the the mining industry is the economics of the process. This section of the study will also compare the economics of roasting, pressure oxidation, and bio-oxidation as means for oxidizing the refractory gold ore at Salmita on a present value basis. Discounted cash flow analysis simply sums the estimated cash flows adjusted for capital depreciation and taxes over the life of a project and then discounts these cash flows by the firms cost of capital. In this way, the firm is better able to identify the capital project that has the least costs over the life of the project after taxes, depreciation, and the timing of cash flows. Also, it facilitates comparison analysis by consolidating all costs into single figure. In short, discounted cash flow analysis simply identifies what the total

of all the cost outflows would be if they could be undertaken in the immediate term, therefore "the discounted cash flow cost". In algebraic terms it is:

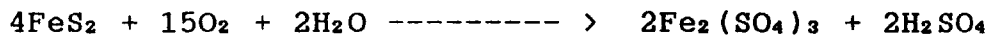
$$DCF = CF_1/(1+k)^1 + CF_2/(1+k)^2 + CF_3/(1+k)^3 \dots CF_n/(1+k)^n$$

where: DCF= discounted cash flow
 k = the firm's cost of capital
 CF = the tax adjusted cash flows
 n = the number of years to the actual cash outflow

Because of the unique nature of the Salmita site and hence the economics, costs will be compared for three (3) processes at a hypothetical site in North Central Nevada assuming an identical ore to that processed at Salmita. Before proceeding, it must be noted and stressed that these figures only apply to the sites and ore in question. Other sites and ores may yield differing results.

The Process

Biological oxidation of refractory gold ores has been well documented among the technical literature (Lawrence and Bruynesteyn, 1983; Bruynesteyn, 1984; Lawrence 1985; Marchant 1986). Primarily, the process is one similar to the familiar process of copper dump leaching with Thiobacillus ferrooxidans. The chemical reactions can be generalized as follows:



In brief, the Thiobacillus ferrooxidans oxidize the sulphides that are inhibiting the cyanidation of the gold ore.

Although, the general process is well-documented, the process optimization and controls are not. Giant Bay Resources has developed a proprietary process utilizing an improved strain of Thiobacillus ferrooxidans that is native to the Salmita site. Both the process and microbe have patent applications pending and further details are unavailable.

Capital costs at Salmita

The following costs have been estimated by Wright Engineers based upon a 1000 ton per day plant and includes all process plant buildings and equipment, but does not include;

- (1) non-process structures
- (2) site access
- (3) site clearing and preparation
- (4) tailing and reclaim system
- (5) power
- (6) water and sewer supply outside the plant battery limits
- (7) the capital costs associated with the mine

These items that have been excluded from the capital cost estimate are site specific and would be presumably the same for all three process alternatives. Considering the fact that this analysis is meant to focus upon comparative costs of the three alternative processes and not necessarily with absolute costs, these costs that are presumed to be identical have been excluded.

ESTIMATED CAPITAL COSTS OF THREE OXIDATION ALTERNATIVES AT SALMITA (IN MILLIONS OF CDN \$)

BIOLOGICAL OXIDATION	PRESSURE OXIDATION	ROAST
\$30.8	\$45.0	\$35.0

As widely reported by the press, the data developed by Giant Bay and Wright Engineers clearly indicates an advantage for bio-oxidation in terms of capital costs. These cost estimates represent a a 13.6% capital cost advantage over roasting and a 46.1% capital cost advantage over pressure oxidation for bio-oxidation at Salmita.

Operating Costs at Salmita

The operating cost estimates for the three alternative processes at Salmita took into account the following items associated with the process plant and equipment;

- (1) power
- (2) fuel
- (3) reagents
- (4) grinding media
- (5) equipment maintenance
- (6) labor associated with staff positions, operators, and maintenance personnel

The following is a breakdown of operating costs at Salmita on a cost per ton basis.

Operating cost summary at Salmita (CDN\$/ton)

Labor	
staff	\$2.57
Operators	4.67
Maintenance	2.34
Camp cost	.99
Power	12.96
Fuel	
cost (f.O.B. Yellowknife)	.98
Transportation to site	.66
Reagents	
cost (f.O.B. Yellowknife)	9.82
Transportation	4.75
Grinding balls	
cost (f.O.B. Yellowknife)	.90
Transportation	.51
Equipment maintenance	1.31
Total	<u>\$42.46</u>

Note in this breakdown of operating costs, the high costs of transportation of fuel, reagents, and grinding media. These transportation costs alone comprise \$5.92 per ton, over 10% of total operating costs at Salmita.

As indicated in the table below, the estimated operating costs for pressure oxidation was \$43.53/ton, 2.5% higher than biological oxidation, and \$49.83/Ton for roasting some 17.4% higher than biological oxidation. Once again, bio-oxidation is the least cost alternative for the oxidation stage. Unlike the capital costs, though, bioleaching has only a marginal cost advantage over pressure oxidation and roasting.

ESTIMATED OPERATING COSTS FOR THREE OXIDATION ALTERNATIVES AT SALMITA
(IN CDN \$ PER TON OF TREATED ORE)

BIOLOGICAL OXIDATION	PRESSURE OXIDATION	ROASTING
\$42.46	\$43.53	\$49.83

The operating costs at Salmita were considerably higher than comparable mines in more moderate climates and at more accessible sites. This was due to the high cost of transportation in Northwestern Canada (\$5.92 Per ton of treated ore). Salmita is accessible by ground transportation only three months per year and only by air the other nine. Also, due to its remote location, power needs could not be met by simply connecting to a utility grid, but instead had to be generated on site using diesel fuel and a generator, significantly raising the power costs (\$.15/Kwh). Furthermore, operating costs included camp costs for the men living at the site rather than at less remote site where the men would commute. Probably most significant were the transportation costs of limestone (limestone had to be transported over 1200 miles to Salmita) to raise the ph before cyanidation. For

sites with limestone readily available, the operating costs of biological oxidation would be significantly reduced (see Nevada operating costs) .

Capital Costs at Hypothetical Nevada Site

All costs at the Nevada site are estimated in U.S. dollars and assume an ore similar to that available at the Salmita site. The estimate is based upon identical assumptions as the Salmita site as stated above. These are summarized below.

ESTIMATED CAPITAL COSTS AT NEVADA SITE (MILLIONS U.S. \$)

BIOLOGICAL OXIDATION	PRESSURE OXIDATION	ROASTING
\$23.1	\$33.88	\$26.17

As these figures clearly indicate, like the Salmita site, bio-oxidation is once again the least cost alternative for the oxidation step in the process. The cost advantage amounts to 13% over roasting the ore to 46.4% over autoclaving (pressure oxidizing) the ore.

Operating Costs at Hypothetical Nevada Site

Operating cost assumptions for Nevada were identical to those in Salmita except where the difference in location made some costs unnecessary. These were primarily related to the transportation costs of Salmita's remote location. As can be seen in the table below, these costs differences are considerable, but bio-oxidation still holds a narrow edge over the alternative processes. The operating cost advantage for bio-oxidation is 4% over roasting and 8.8% Over pressure oxidation.

ESTIMATED OPERATING COSTS OF ALTERNATIVE OXIDATION PROCESSES AT NEVADA
(IN U.S. \$ PER TON OF TREATED ORE)

BIOLOGICAL OXIDATION	PRESSURE OXIDATION	ROASTING
\$18.67	\$20.31	\$19.42

OPERATING COST SUMMARY AT NEVADA SITE
(U.S. \$ PER TON TREATED)

LABOR	
STAFF	\$1.88
OPERATORS	3.45
MAINTENANCE	1.88
POWER	4.49
FUEL	
COST (F.O.B. SITE)	.35
REAGENTS	
COST (F.O.B. SITE)	4.49
GRINDING BALLS	
COST (F.O.B. SITE)	1.17
EQUIPMENT MAINTENANCE	.96
TOTAL	\$18.67

Discounted Cash Flow (DCF) Analysis

It is clear from the figures presented above that bio-oxidation is the least cost alternative from both the capital and operating components of the cost equation at both the Salmita and Nevada site. However, the question still remains

as to how large a cost differential bio-oxidation enjoys over the life of the project. Discounted cash flow analysis can answer this critical question.

For the purposes of this analysis, the following assumptions will be made;

- (1) the life of the project is ten years
- (2) the firms cost of capital is equal to 15 %
- (3) U.S. Tax laws and tax rates extant in 1990 with be utilized for both sites
- (4) all depreciation of assets will be treated as a negative income tax and hence a cash inflow
- (5) the inflation rate averages 6% annually for the life of the project

Based upon these assumptions and the cost estimates from above, the following figures for the discounted cash flow of all costs associated with capital equipment and operation are summarized in the table below.

ESTIMATED DISCOUNTED CASH FLOW OF TOTAL COSTS OF ALTERNATIVE OXIDATION
METHODS AT SALMITA AND NEVADA
(IN MILLIONS OF NATIVE CURRENCY)

	BIO	PRESS.OX	ROASTING
SALMITA	\$93.502	\$105.605	\$109.542
NEVADA	\$47.972	\$58.000	\$51.139

Note that the consolidated figures from a discounted cash flow analysis yield a 17.2% advantage to bio-oxidation over roasting and a 12.9% over pressure oxidation at Salmita, while at Nevada the cost advantages were 6.6% over roasting and 20.9% over pressure oxidation.

Bruynesteyn's Economic Estimate of Bio-oxidation of Gold Concentrates

Albert Bruynesteyn in an article published in 1984 performed a pre-feasibility analysis for refractory gold oxidation using Thiobacillus ferrooxidans. Bruynesteyn applied the conventional air-sparged reactor configuration.

Bruynesteyn estimated the cost for a 400 tpd plant with a 15% sulfur concentrate of which 75% must be oxidized for effective cyanide leaching.

His cost estimates are as follows:

BRUYNESTEYN ESTIMATES OF COSTS OF BIO-OXIDATION (U.S. \$ PER TON)

1. AIR SUPPLY	\$10.91
2. AGITATION	5.40
3. LIMESTONE	6.64
4. LIME	11.48
5. NUTRIENTS	1.60
6. FLOCCULENTS	.80
7. MAINTENANCE SUPPLIES	6.40
8. MAINTENANCE AND OPERATING LABOR	6.00
TOTAL OPERATING COSTS	\$49.23/TON
TOTAL CAPITAL COST (DEPREC.)	\$14.50/TON
TOTAL COST	\$63.73/TON

Equity Silver Mines (Marchant, 1986)

Brad Marchant estimated in 1986 the capital and operating costs of treating 800tpd of arsenopyrite-pyrite bulk concentrate requiring regrind and only partially bio-oxidized to achieve a satisfactory gold and silver recovery.

The ore in Marchant's study was graded at:

- * gold 5.5 Grams/ton
- * silver 90 grams/ton

Marchant's estimates are as follows:

MARCHANT'S CAPITAL COST ESTIMATE		
	1000'S CDN \$	% OF TOTAL
1. TAILING LEACH RECLAIM	290	3.1
2. BULK SULFIDE FLOTATION	683	7.4
3. CONCENTRATE REGRIND	781	8.4
4. BIOLEACHING	3472	37.6
5. HEAT EXCHANGE	202	2.2
6. FILTRATION/WASHING/NEUTRALIZATION	1233	13.3
7. CYANIDATION	15	0.2
8. TAIL DISPOSAL	0	0
9. BUILDINGS, FOUNDATIONS	1120	12.1
10. PROJECT OVERHAUL	1350	14.6
11. CONCENTRATE IMPOUNDMENT	100	1.1
TOTAL		9246
		100.0

MERCHANT'S OPERATING COST ESTIMATE

	CS/TON CONCENTRATES	% OF TOTAL
1. TAILING LEACH RECLAIM	1.08	5.9
2. BULK SULFIDE FLOTATION	1.86	10.1
3. CONCENTRATE REGRIND	1.82	9.9
4. BIOLEACHING	2.73	14.9
5. HEAT EXCHANGE	0.09	.5
6. FILTRATION/WASHING/NEUTRALIZATION	8.33	45.3
7. CYANIDATION AND METAL RECOVERY	1.67	9.1
8. TAILING DISPOSAL	.03	.2
9. MISCELLANEOUS	.76	4.1
TOTAL	18.37	100.0

NOTE: THESE FIGURES DO NOT TAKE INTO ACCOUNT THE COST OF CAPITAL

Gibbs, Errington, and Pooley

In 1985, Gibbs, Errington, and Pooley published the results of their feasibility study of the economics of biooxidation of refractory gold ores. They examined the process and economics of three possible bio-oxidation schemes, including:

- (a) 10,000 tpd of ore residue at 0.3gAu/ton head assay
- (b) 1,250 tpd flotation concentrate at 1.2gAu/ton assay
- (c) 1,250 tpd flotation concentrate at 1.2gAu/ton without bacterial leaching

Assuming a ten year plant life for their stirred tank reactor system, they summarized their results as follows:

ESTIMATED COSTS AND RESULTS

ITEM	A	B	C
1. CAPITAL COST ESTIMATE	\$16,780,000	\$11,260,000	\$9,490,000.
2. OPERATING COST ESTIMATE	\$12,345/D	\$4,085/D	\$3,712/D
3. GOLD RECOVERY	2.7 kg/D	1.35 kg/d	0.75 kg/d
4. 90% WITH BACT. LEACH	(90% OF 3kg/d)	(50% OF 3kg/d)	(50% OF 3kg/d)
5. 50% W/O BACT. LEACH		(90% OF ABOVE)	(50% OF ABOVE)
6. GOLD PRICE (\$/g)	\$11.09	\$11.09	\$11.09
7. REVENUE	\$29,940/d	\$14,970/d	\$8320/d
8. OPERATING PROFIT	\$17,595/d	\$10,885/d	\$4,608/d
9. PAYBACK (340 D/Y OPERATION)	2.8	3.04	6.06
10. OVERALL PROFIT ASSUMING 10 YR. PLANT LIFE	43,100,00	\$25,800,000	\$6,200,000

Although this data is useful in analyzing and comparing these three schemes, it lacks adequate analysis to compare the bio-oxidization of the refractory gold ore to alternative methods as was done above for the Giant Bay test plant, hence it tells us little about the economic feasibility of bio-oxidation. Furthermore, the economic analysis is rather elementary and of limited usefulness due to the well-documented shortcomings of payback period. A more telling analysis would analyze the various schemes by net cash flows to arrive at a net present value (NPV) and internal rate of return (IRR) on invested capital for the three schemes. This has been done and the results are summarized below.

NET PRESENT VALUE AND IRR ANALYSIS

	A	B	C
NET PRESENT VALUE	\$35,711,445	\$19,181,953	\$5,211,105
INTERNAL RATE OF RETURN	61%	52%	29%

NOTE: THIS ANALYSIS ASSUMED A \$400/OUNCE GOLD PRICE IN YEAR ONE, INCREASING AT A 6% RATE OVER THE LIFE OF THE PROJECT AND OPERATING COSTS INCREASING STEADILY BY 6% ANNUALLY. THE NET PRESENT VALUE WAS CALCULATED USING A 15% COST OF CAPITAL AND A TEN YEAR EXPECTED PLANT LIFE.

It becomes apparent from this analysis that processing ore residue with bacterial oxidation has the highest internal rate of return of the three schemes examined by Errington, Gibbs, and Pooley. Not surprisingly, despite the higher capital cost of the bacterial leach plant to oxidize the gold ore, the higher recoveries raise the internal rate of return from 29% without the oxidization step, to 52% with bacterial oxidation. As mentioned above, the weakness of this economic analysis is the lack of comparison with other means of oxidation. What this analysis does indicate to us is that the value of bio-oxidizing mill residue and waste is very high relative to oxidizing concentrates. In this research, the oxidization and recovery of the metal values in the waste had the highest net present value and an extraordinarily high internal rate of return of 61%. Further research and analysis of oxidizing mill waste and residue is presented below from the work of the venerable South African scientist, Eric Livesey-Goldblatt.

Treatment of mill tailing slimes with bacteria

Eric Livesey-Goldblatt (1986) has extensively studied the recovery of residual gold and other metal values from mine tailing slimes. These slimes are the fine particles that had been disposed of by previous milling operations due to the fact the gold and other metal values did not justify further treatment. With higher prices for gold in recent years, some

of these slimes may now be treated bacterially to recover these residual metal values.

Several methods have been attempted to recover these metal values including a combination of processes that include flotation and roasting, followed by cyanidation. In general, these procedures have met with limited economic success due the low recoveries and the high cost of treating the entire waste product. Others have suggested bacterial treatment, but because of the difficulty of getting air, water, and bacteria to penetrate these tightly compacted slimes, they have also met with limited success.

Livesey-Goldblatt developed a procedure to treat these slimes in-situ with bacteria. The difficulty of penetrating the compacted mass posed the greatest hurdle in this process. This was overcome by creating a loose granular material at the surface of the slime (30cm) and treating the slimes in progressive layers. Livesey-Goldblatt used a conventional disc plough pulled by a tractor to loosen the top layer. He then inoculated the slime with either a solution containing bacteria and nutrients or bacteria-bearing slimes. He found that the results were approximately equivalent for both inoculents. He also found that a 15% moisture solution was optimal for oxidization of these slimes, while less moisture inhibited oxidation and more created a mud.

The process required approximately 60 days to achieve 70% oxidation of the pyrite and then recovering 60% of the gold by cyanidation. Livesey- Goldblatt estimated the cost this process as follows:

ESTIMATED COST OF GOLD RECOVERY FROM WASTE SLIMES

	RAND/TON	US\$/TON
1. PLOUGHING, ACIDIFICATION AND REPLOUGH OF THE SLIMES	.90	.41
2. REMOVAL OF STOCKPILE, FROM PILE TO WATER LEACH LIQUID/SOLID SEPARATION AND WASH	.45	.20
3. PUMP TO CYANIDATION, LEACH AND GOLD RECOVERY BY CARBON-IN-PULP	1.50	.68
4. NEUTRALIZATION OF ACID WATER LEACH LIQUOR, LIQUID SOLID SEPARATION, STORAGE OF URANIUM PRECIP., AND DISPOSAL OF LEACHED SLIMES RESIDUE TO WASTE	1.10	.50
5. AMORTIZATION AND OTHER COSTS	.59	.27
TOTAL	R 4.54	\$2.04

The slime treated in this study had the following characteristics.

	OXIDIZED AREA 0-50CM	NON- OXIDIZED AREA BELOW 50CM	
GOLD G/T	0.48	.51	
URANIUM kg U ₃ O ₈ /T		0.20	0.25
PYRITE %	.2-.6	4.50	
JAROSITE AS Fe %	0.5-0.9	nil	
SOLUBLE Fe %	%	.50	trace
QUARTZ %	ca.90	ca.90	
 SCREEN ANALYSIS			
+147 MICRONS	8	10	
+74 MICRONS	23	37	
-74 MICRONS	69	53	
	100	100	

Treating these slimes with .51g/t gold with a 60% recovery, returned revenue of R6.32 (\$11.06) per ton treated and a profit of R1.78 (\$3.12) per ton of slime treated with gold at \$320/ounce. Please note that all U.S.\$ figures above are at 1986 exchange rates.

Other significant developments in refractory gold ore oxidation

Although each of the studies and processes cited above have utilized Thiobacillus ferrooxidans, this ubiquitous micro-organism does have some limitations for use in oxidizing mineral complexes. The primary of these are its slow grow and multiplication rate and its temperature limitations (this is actually a virtue for in-situ applications where temperature is controlled by the ambient environment). Numerous studies have confirmed that Thiobacillus ferrooxidans growth and multiplication is optimized between 30-40°C (Hutchins et al., 1988). At temperatures above 40°C, the micro-organism's activity is dramatically reduced or ceases altogether. This can become a serious process limitation in the oxidation of high sulfur ores or ore concentrates. As mentioned above, the bio-oxidation process is exothermic with the reaction releasing significant amounts of energy that warms the immediate environment. With ores that contain over approximately 5% sulfur or refractory gold ore concentrates that generally contain in excess of this level, this release of energy can raise the temperature in the reaction vats above the threshold for Thiobacillus growth. In these cases, the bio-oxidation process requires additional cooling to maintain temperatures below 40°C and hence additional costs. This increase in costs can narrow the cost advantage of bio-oxidation over the alternatives and in some cases, eliminate it altogether.

The team of Corale and James Brierley at Advanced Mineral Technologies (AMT), Inc. of Golden, Colorado, have a long history of studying thermophilic micro-organisms. These are the organisms that thrive at the high temperatures found in the reaction vats treating ore concentrates or high sulfur ore and render Thiobacillus ineffective. Further potential advantages of using thermophilic bacteria include a reduction in reaction and residence time as the high temperatures hasten the biochemical reactions. Ultimately, if such a reduction in reaction and residence times can be achieved, it could significantly reduce the costs of bio-oxidation even further.

In a study published April 1988, Hutchins, Brierley, and

Brierley (1988), all of AMT Inc., describe a bio-oxidation process developed by AMT utilizing thermophilic micro-organisms. This process addresses the problem found among some refractory ores where cyanidation is indirectly interfered with when the aurocyanide complex is sorbed by organic material and is not available for recovery. This problem has been addressed previously by roasting, pressure oxidation, or chemical oxidation but the high capital and/or operating costs of these processes have hindered the development of some carbonaceous refractory gold deposits.

The AMT process utilizes a micro-organism of the Sulfolobus genus (sometimes utilized for coal de-sulfurization) that is extremely thermophilic (50-80°C) and a moderately thermophilic species of Thiobacillus that exhibits growth activity at 45-55°C.

This research by AMT and others, utilizing thermophilic bacteria, are worthy of note, but the economics of such processes are sketchy, at best. They do have the potential, though, to reduce reaction and residence times and therefore the costs, as these and other micro-organisms and processes are optimized by further continuing research and development.

Gold bio-oxidation conclusions

Biological oxidation has arrived as an economically viable oxidation process to pre-treat refractory gold ores before cyanidation. Although technically the process has been known for over a decade, the process economics have now achieved a level of superiority over the conventional alternatives of roasting and pressure oxidation that it must be given serious consideration whenever conditions make it applicable.

D. Cyanide Degradation Case Study

Introduction

The utilization of cyanide in leaching of gold has proven to be very cost-effective to the production of gold and silver. As the use of cyanide rises in precious metal mining and milling, as well the electroplating industries, the concern for environmental degradation rises proportionately. The mining and electroplating industries continue to seek more effective and less-expensive methods of destroying cyanide in their wastewaters before it can enter the water table or other eco-systems.

Many methods have been attempted and used successfully to destroy cyanide including alkaline chlorination, incineration, ozonation, kastone process, ferro-fero-cyanide precipitation, SO₂ process, the Inco process, copper catalyzed hydrogen peroxide, and prussian blue precipitation, to name just a few . Although each of these processes is effective to varying degrees on a particular range of concentrations and complexes of cyanide, none is effective to all applications. Cyanide destruction remains relatively site specific regarding method, costs and effectiveness. Now, biotechnology offers a new alternative for cyanide degradation with some cost and effectiveness advantages over competitive processes.

This section of the study will focus upon the only commercial scale biological cyanide destruction plant in North America at the Homestake Mine near Lead, South Dakota. A comparison will be made of the economics of this biological process developed by James Whitlock and Terry Mudder of Homestake with the best available alternative process to achieve the desired level of cyanide degradation at the Homestake mine, namely, copper catalyzed hydrogen peroxide.

Historical perspective

The Homestake mine, like many other precious metal mining operations in North America, utilizes cyanide to leach gold from its ore mined in the Black Hills of South Dakota. Homestake's treated and filtered mining and milling wastewater has been discharged to the nearby Whitewood Creek. This small creek, whose flow at times is as much as 60% Homestake wastewater, had been re-classified as a cold water, marginal, trout fishery in the late 1970's by the State of South Dakota. The State of South Dakota then planned to stock this creek with catchable size trout and the cyanide laden homestake wastewater potentially threatened the viability or edibility of these trout. It became essential at this point in time to

raise Homestake's effluent standards to be compatible with the viability of high-level organisms and other potential beneficial uses of Whitewood Creek.

Aware of this need to meet a higher level of effluent standard and just having completed construction of the Grizzly Gulch tailings impoundment dam in 1977, Homestake embarked upon an intensive research program to develop analytical methodologies for toxic parameters of the wastewater and to develop a treatment methodology to meet or exceed the more stringent State of South Dakota cyanide standards. Nearly all available cyanide destruction processes were tested including: acidification/volatilization, ozonation, the Inco process, ion exchange, activated carbon adsorption, prussian blue precipitation, alkaline chlorination, and copper catalyzed hydrogen peroxide.

Chemical and bio-assay effluent evaluations were undertaken in conjunction with each of the above listed cyanide destruction processes. These evaluations lead Homestake's managers to conclude that none of these processes, used singularly or in conjunction with the others, would achieve the necessary effluent standards. A new and innovative method of destroying cyanide in the mine's effluent was necessary if Homestake were to be able to meet the state's standards at a reasonable cost.

The goal of a more efficient treatment of the mine's effluent sufficient to meet the quality standards compatible with the recreational uses of potential trout stream lead directly to the research and development of biological treatment methods. Ultimately, this research and development into biological processes yielded Homestake the only process methodology that met the desired effluent standards.

In the spring of 1981, Homestake began work on isolating and modifying bacterium with the ability to degrade cyanide and thiocyanate. By 1984, Homestake had been awarded United States patents #4,440,644 and #4,461,834 on the process characteristics and the specific mutant strain of bacterium, respectively.

Further research in the analytical methodology, led to further refinements in the total cyanide method, while bio-assay research directed at the toxicity of complex cyanide species determined that the weak acid disassociable forms are the toxicologically significant forms of cyanide.

Utilization of bacteria to degrade cyanide and thiocyanate on a commercial scale had previously never been attempted, even though the scientific literature clearly indicated that

certain strains of bacteria did possess the necessary characteristics to degrade cyanide. The Homestake researchers were able to isolate a single strain of bacteria native to the process waters. They then gradually acclimated these bacteria to increased concentrations of cyanide and thiocyanate, eventually developing a mutant strain with the necessary capacity to degrade the levels of cyanide present in the Homestake mine wastewater.

The Homestake mine discharges a maximum of 21,000 m³/d (5.5 Mgd) from its cyanidation mill process and mine discharge. The following are the key physical characteristics of this wastewater:

WASTEWATER CHARACTERISTICS AT THE HOMESTAKE MINE 1986

PARAMETER	MINE WATER	TAILINGS IMPOUNDMENT WATER
THIOCYANATE	1.00-16.00	110.00-240.00
TOTAL CYANIDE	0.10- 0.50	7.00- 30.00
METHOD-C CYANIDE	0.02- 0.10	4.00- 20.00
IRON	0.10-10.00	1.50- 6.00
COPPER	0.07- 1.60	1.40- 6.00
NICKEL	0.01- 0.04	0.20- 0.40
ZINC	0.01- 0.10	0.01- 1.50
AMMONIA-N	5.00- 6.00	LESS THAN 1.0
PHOSPHOROUS	trace	trace
PH	5.00- 6.50	7.00- 9.50
TEMPERATURE	70 - 85°F	34.7°F

ALL VALUES IN MG/L EXCEPT TEMPERATURE AND PH

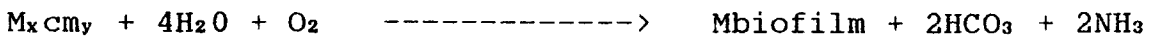
Note: The actual wastewater ratio is varied throughout the year from 70/30 mine/tailings impoundment wastewater ratio in the winter to 50/50 mine/tailings impoundment wastewater ratio in the summer.

The biological cyanide destruction process (Whitlock and Mudder, 1986)

As mentioned above, Homestake was able to isolate a strain of bacteria native to the process waters and then improve it to the point where it could effectively degrade cyanide to the desired levels. These bacteria were found to have minimal

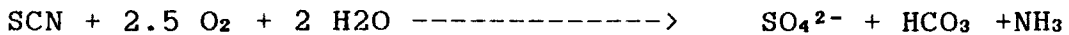
growth requirements and could best be described as aerobic heterotrophs. Their metabolism is respiratory and their optimal ph range is between 7-8.5, while optimum growth occurs in the temperature range of about 30°c with limitations on growth met at the upper and lower bounds of 5° and 42°c. The bacteria does not reduce nitrites or nitrates and H₂S is not produced. The bacteria, Pseudomonas paucimobilis, oxidizes free and complexed cyanides to carbonate and ammonia and the metals in the solution are adsorbed, ingested and precipitated.

Cyanide metal complexes are degraded as in the following equation:

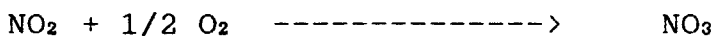
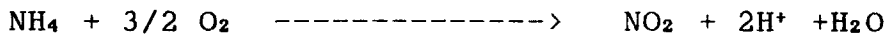


Where m represents heavy metals which are removed via adsorption in the biofilm.

Thiocyanate degradation is rapidly accomplished as in the equation below:



Following the degradation of thiocyanate/cyanide and metals removal, the ammonia produced as a by-product from cyanide oxidation must be de-toxified. This is accomplished in the nitrification stage by means of a common pair of aerobic, autotrophic bacteria (Nitrosomonas and Nitrobacter). The ammonia is oxidized to nitrite slowly and then rapidly to nitrate. The conversion of ammonia to nitrate proceeds as follows:



The microbial flora in the degradation stage and in the nitrification stage are normally non-competitive as limited by the change in thiocyanate/cyanide and ammonia concentrations. Thiocyanate and cyanide act as a food source for the degradation stage bacteria and are toxic to the nitrifying bacteria. Ammonia acts a food source for the nitrifiers and along with the diminishing food source, may act to control competition from the cyanide degrading bacteria.

The treatment plant is an aerated, attached growth,

biological system incorporating the use of 48 rotating biological contactors followed by clarification and pressure sand filters with dual media beds. The wastewater consists of a blend of both tailings impoundment decant water and mine waters with predetermined ratios controlled by a thiocyanate monitor developed by Homestake. The wastewater contains most of the nutrients necessary to the bacteria. Initially, phosphorous and carbonate were supplemented, but further optimization of the plant have made regular chemical additions unnecessary.

The 48 rotating biological contactors are arranged in a mirror image plant design with 24 discs per side. The wastewater flow is perpendicular to the disc with five discs per train. In general, the first two discs per train accomplish thiocyanate/cyanide removal and metals accumulation and the remaining three discs accomplish nitrification.

Operating Performance (Whitlock, 1987)

Start up of the full scale plant was initiated in August of 1984. Effluent from the initial pilot scale plant was utilized as a seed source of inoculum for the commercial scale plant. Nitrification stages of the process were seeded with municipal activated sludge to promote nitrification.

Within 30 days, stabilization of the wastewater was accomplished with a relatively consistent effluent quality. Whitewood creek water quality demonstrated a rapid improvement. Studies conducted by the South Dakota Department of Game, Fish and Parks and the Department of Water and Natural Resources demonstrated that various species of trout were moving into the discharge zone for the first time since mining was initiated at the site.

Removal rates of wastewater contaminants varies with the plant operation, however, the following removal rates have been established:

thiocyanate	99-100%
total cyanide	91-95%
weak acid dissociable cyanide	98-100%
copper	93-98%
ammonia	95-100%

Process economics

When Homestake began its search for a method to process its mill and mine waste waters, they examined and analyzed the full range of cyanide degradation methods. Of these methods, they found none that would achieve the desired levels of cyanide degradation in their wastewater. This spurred the research and development into biological cyanide wastewater treatment.

Of the initial methods examined--many for which pilot scale plants at the mine were built--the method found that achieved the highest level of cyanide degradation in their wastewaters was copper catalyzed hydrogen peroxide. Although other methods may have been less expensive, either from the capital side or operating side of the cost equation, they were unable to approach the level of cyanide degradation deemed necessary and desirable by Homestake and the State of South Dakota.

The following cost analysis is based upon data supplied by Homestake and it's chief analytical and assay chemist, James Whitlock, for the copper catalyzed hydrogen peroxide process and the biological degradation process.

ESTIMATED AND ACTUAL COSTS OF CYANIDE DESTRUCTION TREATMENT METHODS AT HOMESTAKE GOLD MINE, LEAD SOUTH DAKOTA (Whitlock, 1988)

COST	CAPITAL COST	OPERATING ¹	DCF)
			(1 9 8 7 \$)	
HYDROGEN PEROXIDE ²	\$16,000,000	\$4131/DAY	\$16,624,662	
BIOLOGICAL ³	\$10,000,000	\$2935/DAY	\$11,249,541	

¹ INCLUDES CAPITAL DEPRECIATION

² ESTIMATED FIGURES FROM 1983

³ ACTUAL FIGURES FROM 1987

As depicted in the above table, biological cyanide degradation is less expensive from both the capital (60%) and operating cost (29%) perspective than hydrogen peroxide to achieve the level of cyanide destruction necessary and desirable in the Homestake mine wastewaters. When this data is compared from a discounted cash flow perspective, our model indicates that the biological cyanide destruction is 32% less expensive over the life of the project. The assumptions built into this model are similar to those built into the other dcf models used throughout this study. Explicitly, these are as follows:

- (1) the cost of capital is 15%
- (2) the inflation rate is 6%
- (3) all extant tax and depreciation laws in the U.S. at the time of this analysis are applied

Although it was originally estimated that the process would require regular additions of phosphorus and carbonate, operating history has proven that chemical additions are unnecessary on a regular basis, further reducing the operating costs below original estimates. As the plant has now operated for nearly four years, further optimization has successfully reduced the costs of wastewater treatment. The table below summarizes Homestake's experience with biological degradation from 1985-1987. All costs include labor, supervision, power, gas, maintenance and capital depreciation.

COST HISTORY SUMMARY OF BIOLOGICAL CN DESTRUCTION AT HOMESTAKE
1985-87

YEAR	PER POUND CN TREATED ¹	PER TON	PER MILLION ORE MILLED ²	GALLONS EFFLU ³
1985	\$5.35	\$1.09	\$1520	
1986	\$3.70	\$0.71	\$1320	
1987	\$2.50	\$0.54	\$ 911	

¹ TOTAL POUNDS OF CYANIDE (CN) TREATED INCLUDES THIOCYANATE AND ALL METAL COMPLEXED CYANIDES AS TOTAL POUNDS CN

² BASED UPON 1987 YEARLY TONNAGE OF 2.347 MILLION TONS

³ BASED ON AVERAGE DAILY EFFLUENT FLOW OF TREATED WASTEWATER AT 3.832 MILLION GALLONS PER DAY OR 1.4 BILLION GALLONS PER YEAR.

Note that the costs per millions of gallons of water treated have fallen over 40% from 1985 to 1987. Even greater cost reductions have been realized on a cost/ton of cyanide treated (53%) and cost per ton of ore milled (50%).

Total annual costs of operating the wastewater treatment plant in 1987, excluding capital depreciation were only \$767,990 accounting for just 1.3% of total milling and mining costs at Homestake. As the costs of treating the effluent at Homestake are largely fixed, economies of scale can be realized when the volume of mined ore increases. In this instance, treatment costs will remain relatively stable and would result in further reductions in the cost of treatment per gallon of effluent.

Biological Cyanide Degradation Conclusions

Biodegradation of complexed cyanides has been proven to be both technologically and economically viable and the potential for further applications beyond the Homestake mine appear to be great.

Although this process appears to be very effective at Homestake, this process methodology may have to be adjusted to a site-specific set of parameters. Furthermore, the active degrading micro-organism, Pseudomonas paucimobilis, may need to be adapted to optimize its growth and effectiveness at degrading cyanide under different concentration and other operating parameters. Despite this, the significant cost savings realized by Homestake are nothing less than impressive.

The advantages of biological degradation over physical or chemical cyanide degradation are as follows (Whitlock, 1987)

- (1) treatment efficiencies equal or exceed those of chemical treatment
- (2) plant construction and operating costs are significantly lower
- (3) resistance to shocks and upsets as well as recoveries from upset appear to be superior
- (4) total dissolved solids and sludge production are likely to be lower

- (5) the potential exists to develop small scale plants without the need for electrical power or chemical addition.
- (6) significant economies of scale may be realized may the volume of mining and hence eluent increases. Costs are relatively fixed and greater volumes do not necessarily increase costs proportionately.

A final note: cyanide destruction systems, similar to that developed at Homestake, demonstrate only the potential of biological systems for clean-up or mitigation of mining and milling waste effluent. Biological systems have the key advantage of tending toward self-regulation, in other words, it may be possible to establish a particular flora in a waste stream or site and the system then becomes independent of human intervention. As cited by James Whitlock (1987) , the potential does exist to develop plants that do not require electrical power or chemical addition--unlike chemical and physical processes that not only require continuous human intervention but continuous input of reagents, chemicals, energy, etc. The Homestake biological system is beginning to approach such a passive system, as the input of chemicals is now superfluous to the process. This is primarily due to the fact that biological systems become/are complex eco-systems that soon develop their own self-regulating mechanisms. The complexity of these systems exceeds the complexity of systems that man can manage and regulate.

This characteristic, self-regulation and passivity, may become increasingly important as the liability of mine sites and effluent disposal lengthens in time. As an example, Wixon and Davies (1985) point out that ancient rock and chat tips connected with old Roman lead-zinc mines in Wales are still causing contamination problems that must be corrected at considerable cost to today's taxpayers, some 2000 years later. If this contaminated run-off and seepage must be collected in perpetuity from today's sites, the cost and liability of doing so may become astronomical. Biological eco-systems, established as a wastewater-effluent clean-up method during the life of the mining operation, may achieve a level of self-regulation and passivity to mitigate such problems indefinitely--even after the ore has played out and the operation has closed down.

The costs of biological degradation of cyanide at Homestake appear attractive in the present term. Moreover, the economics from a long-term environmental liability standpoint may be even more attractive. Conceivably, the mining site may be stabilized after the term of mining by introducing a native and/or mutant strain of bacteria that utilizes the waste/run-

off as an energy and food source. Such a flora of microbes has the potential then of indefinitely mitigating the long-term environmental impacts of the site with little or no human intervention and hence little or non-existent operating costs. The practical utilization of such systems will certainly require additional research and time, but Homestake has made a tremendous contribution toward the develop of such systems with its cyanide destruction process. Further such efforts as Homestake's will likely yield additional cost savings in the processing of process wastewaters

E. Biological Coal Desulfurization Case Study

Introduction

The U.S. has once again achieved a high dependence upon foreign imported oil in the late 1980's. This is in spite of the harsh lessons of a ten-fold increase in oil prices in the decade of 1970's, the Arab oil embargo, and the Iranian revolution. Presently, the U.S. has returned to importing approximately 45% of its total petroleum consumption, exceeding our level of dependence on foreign imported just preceding the Iranian revolution of February 1979. This has come about despite the fact that the U.S. has the largest total reserves (364 billion tons) and largest recoverable reserves of coal of any nation on earth.

Several factors, though, have inhibited our development and exploitation of our coal resources to their fullest potential. Among these, one of the most significant is the environmental impact of coal combustion. Coal is far from homogeneous and besides its content of hydrocarbons, it contains varying amounts of oxygen, sulfur, nitrogen, and trace minerals. It has been largely the presence of this sulfur in coal that represents the greatest hurdle to exploitation and further utilization.

When coal is burned, the sulfur in the coal contributes to the atmospheric load of sulfur dioxides and particulate matter. This sulfur dioxide then combines with water molecules in the upper atmosphere and creates a form of sulfuric acid that then falls as "acid rain".

It is estimated that the U.S. alone releases 27 million tons (Gordon, 1984) of sulfur dioxide into the atmosphere every year and approximately 2/3 of that is produced by coal burning utility plants.

The environmental impact of acid rain has been well documented in both the scientific and popular literature and will not be reiterated here. It will suffice to simply point out that the political agenda of both federal and state officials include further pressure for more restrictive regulation of sulfur dioxide emissions and the industry must prepare for a future where these regulations may severely limit their emissions of sulfur dioxide.

It becomes apparent then that the full utilization and exploitation of America's coal resources has been limited -- and will become more so in the near future -- to the ability of the utility and coal industry to either:

- (1) reduce emissions through improved flue gas clean-up
- (2) reduce sulfur content before combustion

The success of these industries to do so, will have a significant impact upon the U.S. ability to once again wean ourselves from the vagaries of the geo-politics of the Persian Gulf as well as maintain a safe and clean environment.

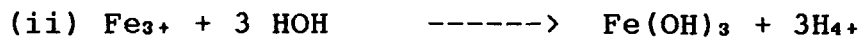
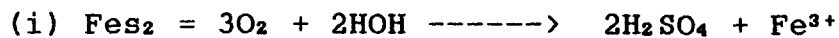
A number of coal de-sulfurization processes have been developed and utilized and these have been applied to about 35% of U.S. coal before being burned (Shepard, 1985). Of the coal cleaning processes, physical coal cleaning processes are most commonly used. Another coal cleaning process has been developed utilizing the sulfur oxidizing capability of the ubiquitous microorganism, Thiobacillus ferrooxidans. This coal desulfurization process has carried the hope and promise of a significant segment of the biohydrometallurgy community despite it's ability to only oxidize the inorganic sulfur and its ineffectiveness on that organic component of the sulfur in coal (the alternative processes also remove only the inorganic sulfur as the organic sulfur is bound in the coal matrix leaving it very difficult to remove without severely reducing BTU output). This segment of the study will attempt to compare the costs of the most commonly utilized and prospective physical coal de-sulfurization processes with biological coal de-sulfurization.

The microbial de-sulfurization process

This segment, in brief, will attempt to describe the biological de-sulfurization process. This is not meant to serve as a substitute for a thorough scientific or engineering treatise on the subject, but simply to familiarize the lay reader on the basics of the process.

Sulfur in coal is present in two major forms: (1) sulfide minerals such as iron pyrite (FeS_2) may be dispersed throughout the coal; (2) organically bound sulfur is present as an integral part of the coal matrix. Iron pyrite is a cubic crystal and is not an integral part of the chemical structure of coal. The organic sulfur is chemically bonded to carbon and cannot be removed without destroying the integrity of the coal. The inorganic sulfur can be removed by various techniques without destroying the integrity of the coal. The ratio of this inorganic coal to organic coal is not constant, but the amount of pyritic sulfur usually exceeds that of the organic sulfur in high sulfur coals (Dugan, 1986).

Thiobacillus ferrooxidans and some other micro-organisms are able to utilize both the sulfur and iron in pyrite and capture the energy released to support their growth. The FeS₂ is ultimately oxidized biologically in the presence of air and moisture to H₂SO₄ and iron hydroxide. The sulfur reaches virtually the same chemical endpoint as in the combustion process. However, microbial desulfurization can be controlled by containing the process in a vat, tank, lagoon, etc. The resulting sulfuric acid and dissolved mineral by-products can be easily removed so that they do not contaminate the environment. The net effect of oxidative microbial metabolism is the conversion of extremely insoluble FeS₂ to water soluble H₂SO₄ and iron hydroxide in accordance with the following generalized reactions:



Process and Economic Limitations of Biological Coal Desulfurization

- * the relatively long residence/reaction time (8-12 days)
- * the inability to remove organic sulfur

Advantages of Microbial Desulfurization

Dugan (1986) described some of the advantages of microbial desulfurization.

- * The capability of removing finely dispersed pyrite without considerable loss of coal
- * pre-combustion removal could be accomplished at or near mine sites, thereby reducing transport costs of undesirable weight (pyrite and ash) and keeping undesirable products away from urban areas
- * the process removes some ash via acid leaching
- * the by-products may have value as a flocculation aid in domestic waste water treatment
- * the low cost operating costs of the process once the capital

investment is made

- * the potential for "polishing " coal that has been partially cleaned by another process
- * the potential recovery of high sulfur coal mines from settling lagoons
- * the process is compatible with slurry pipeline transport of coal and emerging technology of wet combustion

Although the economics of biological coal de-sulfurization have remained controversial with opinion polarized with the advocates who cite its low cost and its detractors who cite its relatively long residence time, its process economics appear to be comparable with physical coal cleaning technology. Note that the estimated costs cited by Bos, et al. contain a range of estimated costs. The low estimate places biological coal de-sulfurization among the lowest cost processes, while the high estimate puts it among the highest cost. Although the capital costs of biological de-sulfurization are relatively high, the operating costs are extremely low. This would imply significant economies of scale making it ideally suited to large operations and inappropriate to small operations. Part of the difference in the estimates of cost per ton by Dietz and Bos is related to plant scale. The plant scale estimated by Dietz is approximately 3 times the size of that estimated in the Bos study. The economies of scale of this process may have been at work in these differing estimates. It should also be pointed out that the estimates of the cost per ton of cleaned coal are not entirely comparable as the biological processes and the physical processes utilized different coals and achieved comparable, but different levels of de-sulfurization. Despite this problem, they represent the best available data at this point in time.

Biological Organic Sulfur Coal Desulfurization

In 1985, Isbister and Kobylinski of Atlantic Research Corporation published the findings of their research on organic de-sulfurization of coal utilizing a proprietary micro-organism they would only identify as CB-1 (coal bug-1). Others such as Kargi, Kikret, and Robinson (Kargi et al.,1982) have also published research indicating the usefulness of thermophilic bacteria in the removal of organic sulfur. These micro-organisms reportedly can remove a portion of the organic sulfur from coal. Isbister and Kobylinski's CB-1 and Kargi, et al.'s Sulfalobus acidocaldarius, primarily attacks thiophenic sulfur in coal, removing the sulfur from the coal as a water soluble sulfate. Isbister and Kobylinski

report that in bench scale tests, the microbe reportedly removed 47% of the organic sulfur from a coal, but they do concede that the level of coal removal is highly dependent upon the coal type, particle size, and surface properties.

They--Isbister and Kobylinski-- estimated in 1985 that cost of producing coal of approximately 10% moisture after de-sulfurization was \$25.50 per ton. To dewater the coal to 30% moisture, they estimated the cost at \$21.09. It must be noted that this process, at best, removes slightly less than 50% of organic sulfur, while the previously cited biological processes were removing 90% of the inorganic sulfur. The primary significance of these studies was not their process economics, but rather the technological possibility to remove both organic and inorganic sulfur from coal, biologically.

Process economics

As pointed out by Dugan (1986) and Finnerty and Robinson (1986), the economics of biological coal de-sulfurization must be not only compared to other de-sulfurization processes but also to other compliance strategies on the part of utilities. Utilities do not necessarily want clean coal, they want fuel that performs well, allows them to meet air quality standards, and results in minimum generation costs (utilities spend considerable sums to not only reduce emissions, but also to reduce maintenance costs that result from the partial combustion of the ash content in coal). Coal cleaning is but one strategy for meeting these goals. Utilities have other options as well, all of which they consider as they make coal purchasing decisions.

Utilities can burn coal with high levels of sulfur and ash and then strip these impurities in the combustion chamber or from the flue gas with pollution control devices. Conversely, utilities may choose to spend more on low-sulfur western coal-- naturally low in impurities-- enabling them to save money by installing less sophisticated pollution control devices. This low-sulfur coal, presumably because of greater demand and lower pollution control devices, would sell at a premium to the high-sulfur coal. This premium, if we assume an efficient market, would be then equal to the costs associated with the pollution control devices. This being the case, the low-sulfur coal premium would indicate the magnitude of the costs of de-sulfurization in the intervening decade (1978-1988). Low sulfur coal companies in the West bid aggressively for leases on lands containing low sulfur coal, primarily in Wyoming and Montana, in the early 1980's. They then rapidly and aggressively expanded production on expectation that the fear of further oil price increases and sulfur dioxide emissions would increase demand and the premium for their low-sulfur

coal. In the intervening years, the all too familiar story of a worldwide energy glut has drastically changed market conditions from that expected by the coal company planners. Furthermore, the anticipated concern about acid rain was postponed and dissipated. Consequently, the coal companies were left with large capital investments and federal leases that must be kept active. These have provided a strong financial incentive to these low-sulfur coal producers to maintain production despite low prices and over-production. As a result, the cost premium that Dugan notes in 1978 has evaporated and in 1987 the cost differential between low-sulfur and high sulfur coal was imperceptible when adjusted for BTU content (Hayward, 1988)

Coal desulfurization conclusions

The combustion of coal in the U.S. is a major source of energy. In 1984, U.S. utilities burned 664 million tons of coal and generated over 1.3 trillion kwh, or approximately 55% of the nation's electrical energy. If the U.S. is to expand the production and utilization of this domestic, plentiful, and secure energy source, new and better processes will have to be developed to clean the coal, not only to reduce sulfur dioxide emissions, but also to reduce the cost of generating electricity.

Biological desulfurization provides a new alternative to cleaning the sulfur and ash from "dirty coals" and providing the promise of clean combustion of coal and ultimately the further development and exploitation of America's coal reserves to meet our present and future energy needs. According to the best cost estimates available, the economics of biological coal de-sulfurization are competitive with that of the conventional physical processes, the most commonly used coal de-sulfurization processes at present. It appears that the process has considerable economies of scale making it appropriate to very large applications. Furthermore, if the biological de-sulfurization of the inorganic component of coal could be combined with the biological de-sulfurization of the organic component at a reasonable cost, it may make a very compelling case for adopting biological methods to coal de-sulfurization to utilities and other coal consumers.

The demand for new coal fired power plants has dwindled in recent years to the point of almost being non-existent in the current energy glut. At the same time, the premium for low-sulfur coal has evaporated in the fiercely competitive coal markets. Existing power plants are largely meeting existing emission standards either by employing one or a combination of flue-gas scrubbing, burning low-sulfur coal, or physical

cleaning processes. This being the case, the present energy and geo-political environment will limit the commercialization of biological desulfurization in the near-term.

V. Future Commercial Applications of Biohydrometallurgy

INTRODUCTION

Just as biohydrometallurgy's preceding three decades have been marked by a focus upon the scientific and engineering

aspects of the iron-oxidizing bacteria Thiobacillus ferrooxidans, the next decade will likely be marked by the rapid and widespread commercial developments in biomining. Biohydrometallurgy has held significant promise for the mining industry for those three decades, but only now has the necessary critical mass congealed to make this long-anticipated leap to widespread commercial adoption. This critical mass includes sufficient commercial success to have converted advocates among the mining industry and most recently, the confidence of the financial community that it holds the promise of significant profits. The next decade then will be one of revolutionary change in the mining industry, as resource recovery techniques are likely to change more in the next ten years than in the past millennium. For this reason, it is necessary now to step back and examine the future of these biological processes and the resource recovery industry. In this way, we may be able to avoid several technological dead ends and focus the industry's efforts on those areas that are likely to pay the greatest dividends.

In an effort to identify those biological processes that will be commercially viable for the resource recovery industry, some intellectual groundwork must first be laid. First, note that I have avoided using the term "mining" industry when I discuss the future. This is intentional and is a reflection of the magnitude of the change biotechnology will have on this industry. In this new environment of metal and mineral recovery, the term mining will seem anachronistic. Contemporary mineral and metal recovery techniques are more similar than dissimilar with those mining technologies utilized over the last three thousand years. This industry has made enhancements in the level of sophistication to the technology that was initially used in the ancient world, but has failed to transform this technology significantly. For purposes of contrast, during the same period of time, both health care and information processing technology have revolutionized their functions in industrial society. It does not require a historian of technology to comprehend that health care and information processing technologies have radically transformed not only their tools, but also the way we think and understand these functions of industrial society. Unfortunately, the same cannot be said for mining technology. Biotechnology will provide this industry with an entirely different conceptual paradigm of mineral or resource recovery as these ancient techniques and technology become obsolete. Thus, I prefer the term "resource recovery" to signify the industry's post-biotechnology advent and adoption.

Second, as Robert Noyce (1989), founder of Intel, and now CEO of Sematech (the semiconductor industry's joint research and development effort), has so concisely stated:

A lot of things are technologically possible, but only economically feasible products will become a reality. Where costs can be pushed down rapidly, great new vistas arise.

This statement is as pertinent to biotechnology in the minerals industry as it is to the semiconductor industry. Technological developments in themselves make for excitement in the laboratory and in academic journals, but only those that can contract costs profoundly will have the impact on industry and society that this analysis is attempting to identify. Many biotechnology processes will or have become technologically feasible, but history indicates that it is not strictly a matter of simple economics, but rather of technology and techniques that can compress costs sharply and open "great new vistas" that transform industries and society. It is techniques and processes capable of opening these new vistas that this analysis seeks to identify.

Third, this analysis is attempting to identify only those processes that will survive the long-term in the industry. In other words, those techniques or processes that may gain some economic advantage in the short-term--but lead to technological or commercial dead ends--will be filtered out. As Herbert A. Simon (1977), the Nobel Laureate economist and cognitive scientist so aptly pointed out:

Prediction is easier (and presumably more accurate) if we do not try to forecast in detail the time path of events and the exact dates on which particular developments are going to occur, but to focus, instead, upon the steady state that the system is tending.

An example from history of such analysis is provided by computer technology. The computer was invented in 1840 by Charles Babbage (Mergerison, 1978) and although many technological improvements were made upon his machine over the next century (each having economic advantages over the previous system), none had the effect of sharply and significantly reducing the cost of computing. This was because none of these technological enhancements addressed the primary economic bottleneck of computing, that is, the limitations of analog systems. As a result, to have projected into the future these analog devices would have missed the steady state that this system was tending. It took the insight of Allan Turing in 1936 to identify this barrier and suggest digital systems as the solution. Turing's analysis in 1936 then is responsible for having made these machines a ubiquitous part of our modern world as computing technology approaches its steady state. This analysis attempts to identify the steady state for the

resource recovery industry by identifying those biological resource recovery processes that address the needs of the industry in a manner that will dramatically reduce costs.

In order to properly and accurately identify those processes that will shape the future of the resource recovery industry, it becomes incumbent to undertake two (2) key tasks. First, we must identify where the mining industry's problems and economic "bottlenecks" occur, as Turing did with the computer. These are the production or process areas that have resisted significant cost reductions by the application of new technology or where costs have increased as a result of changing conditions. It is here that new technology can have its most significant impact. Second, we must identify those characteristics of biohydrometallurgical processes that will provide us with the opportunity to reduce costs of resource recovery sharply in order to reveal these "great new vistas" that Mr. Noyce refers to. It is the intersection of these two sets-- those biological processes or process characteristics that address directly the industry's greatest barriers to significant cost reduction--that is likely to unveil the identity of the successful commercial processes of the steady state resource recovery industry.

ECONOMIC PROBLEMS AND "BOTTLENECKS" FACING THE MINING INDUSTRY

First let's address the issue of economic bottlenecks. Although it has been well-documented, it is necessary here to restate the changing nature of the metals industry in the U.S. and the world. Undoubtedly, new mineral deposits will be found that are relatively high grade in the ensuing decades, but these will be the exception and not the rule. From a global and national perspective, ore grade will continue to decline as high grade ores are depleted. Since the turn of the century, the average ore grade for copper in the U.S. has declined from approximately 2% (U.S. Geological Survey, 1914) to the present .6% (U.S. Bureau of Mines, 1988). Similar patterns can be found in other base and precious metals as the high grade ores are depleted. This slow, but steady decline in ore grade will make more and more deposits uneconomical to mine by conventional means in the near future. Simply put, these lower grade ores lead to higher production costs because the firm incurs the expense of handling more material to produce an equivalent amount of metal. In the copper industry, over 50% of the energy consumed and 2/3 of the capital costs are associated with the removal of the ore and beneficiation by conventional processes (Agarwal et al., 1980). With high grade ores, the metal values in the ore exceed these costs but as ore grade declines, there becomes a crossover point where the ore extraction and beneficiation costs exceed the value of the metal. See Figure 1. At this point, conventional mining

techniques are no longer effective and lower cost processes become necessary. The industry may be driven beyond this crossover point by (1) a reduction in ore grade, (2) lower metal prices, (3) higher input prices, or any combination of the above.

Notwithstanding the recent attempts by the mining industry to reduce energy consumption, the industry remains relatively energy intensive. For instance, the production of a metric ton of copper by conventional mining techniques requires approximately 100 million BTU's of energy (Pitt, 1980) of which 1/3 to 1/2 are associated with ore extraction and beneficiation (U.S. Bureau of Mines, 1988). Despite the relative stabilization of energy costs, the mining industry must be wary of a sudden and sharp rise in the cost of energy in the future. Any sharp increase in energy prices would severely inhibit the industry's ability to sustain their current prosperity. The industry must not be lulled to sleep by the pronouncements of OPEC's demise and the energy glut, as neither of the energy crises of the 1970's were strictly a result of supply and demand, but rather Middle Eastern politics. Considering the continuous political instability of the Middle East, any somnolence in the effort to reduce energy consumption by the industry could be met with an abrupt arousal and a sea of red ink.

Concern and financial liability associated with environmental damage from mining activities seems to be following an inexorable path. This trend seems to have accelerated in the preceding year, although the environmental conscience of the mining industry had been raised several times in the last decade by a number of legal and regulatory changes. Most significant among these was the limitation on sulfur dioxide emissions from smelters. This measure alone cost the copper industry over \$2 billion in capital costs (MacDonnell, 1987) for air pollution control and 10 to 15 cents per pound of copper produced (Everest, 1985). If the EPA holds mining companies financially liable for the clean-up costs of abandoned mining sites that have achieved Superfund site status and this financial culpability becomes more of a certainty, environmentally superior techniques will swiftly become economically superior techniques.

Labor costs of the mining industry must also be addressed. Although the industry has been successful in reducing labor costs and raising labor productivity in recent years, if several recent demographic and economic studies are correct, labor costs will once again begin rising sharply in 1990's as a result of an expected labor shortage. This anticipated labor shortage in the U.S. is the result of the large number of "depression babies" leaving the labor force as they reach retirement age combined with the effects of the "baby bust"

of the 1960's and 1970's. These demographic trends will combine to produce fewer new members of the labor force in the 1990's and beyond. Just as with any commodity, if demand continues to grow while supply remains tight, the price rises. This labor shortage is expected to occur most acutely among the skilled segment of the labor force.

Academicians are often accused of talking among themselves and disregarding the fact that a real world exists beyond our ivory-covered walls. The result is often academic analyses that are sterile and have little relevance to what is actually happening in the field. In order to thwart this type of intellectual incest and augment our analysis of the mining industry, we at Montana College of Mineral Science and Technology conducted a survey of the two hundred (200) major mining companies in North America (Debus, 1988). This survey was conducted to acquire mining executives industrial perspective on some of these key issues. In an attempt to receive responses from that key company official with the broadest perspective of the industry, the survey was directed to the chief executive officer (CEO) of these firms. Assuming that these CEOs know and understand their industry, then several of their responses to this survey have relevance here.

Critical and germane to this analysis of economic bottlenecks of the mining industry, the CEOs were asked to identify that segment of their production process least competitive with foreign producers. The responses gave us a clear picture of how these CEOs view the relative competitiveness of the various production segments of the industry. Over a third of the respondents (37%) indicated that smelting and refining was the least cost competitive of their production processes, followed closely by 28% who responded that ore extraction was least cost competitive. No other segment of the mining industry production process was viewed as the least competitive by more than 10% of the chief executive officers. This data suggests that the majority of the individuals who operate North America's major minerals companies, view smelting and refining and ore extraction as their greatest economic bottleneck. These two areas that have hindered the industry's efforts to reduce costs then may be perceived as providing the greatest opportunity for biohydrometallurgical processes. Processes that address these areas cost-effectively are more likely to gain commercial acceptance as they confront the perceived barriers identified by the industry leaders. It is worth noting here that the biological mining process with the greatest commercial success to date, copper leaching, has addressed both of these issues and hence has been able to reduce copper production costs by half and gain widespread acceptance. Such a lesson should not be lost to us in our future planning and development by the

biohydrometallurgy community.

In summary, ore grade continues to decline and the mining industry remains relatively energy intensive, spending large sums to transport waste rock and process ores. The industry is also likely to experience accelerating labor costs over the next decade. Environmental regulations are expected to continue to become more restrictive and therefore increase mitigation costs while the industry leaders believe that smelting and refining and ore extraction provide the greatest barriers to reducing production costs.

KEY ECONOMIC CHARACTERISTICS OF BIOHYDROMETALLURGICAL PROCESSES

A brief review of the present state of commercial biotechnology in the resource recovery industry is necessary here. In terms of dollar value, the recovery of copper from dumps, heaps, and in-situ provides the overwhelming success story to this field. In 1989, over 25% of all copper produced in the U.S. will come from biological processes, or over \$650,000,000 (Holmes et al. 1988). This copper recovery from biological means can be attributed to the work of the ubiquitous bacteria Thiobacillus ferrooxidans. First exploited commercially in 1752 at Rio Tinto and first identified by Bryner et al. in 1954, this organism continues to generate the bulk of the commercial and research interest in this area. These include the exciting new commercial developments in oxidizing refractory gold ore, desulfurizing coal, and recovery of uranium. In short, up to the present this bacteria has been the "workhorse" in commercial biological resource recovery despite the fact that we still understand so little about its interaction with pyrite. This means that much of the commercial research and development in this field has been engineering systems to optimize the iron-oxidizing capability of this organism.

Other processes that have gained at least some small level of commercial success include the biosorption of metals from aqueous solutions and the biological destruction of cyanide. This is not to downgrade or ignore a whole host of other biological processes for resource recovery, but they simply have not yet gained commercial adoption or acceptance to any substantial or sustained degree.

The second task necessary to complete this analysis requires that a discerning inventory of the key attributes or characteristics of the commercially successful biohydrometallurgical processes be taken. The fundamental criterium is to identify the characteristic primarily responsible for the reduction in costs or improved capability that can be credited for the success of the process. An

analysis into the economics of these processes reveals the following key attributes were critical to their commercial success:

1. in-situ capabilities
2. lower energy costs
3. lower capital costs
4. lower labor costs
5. ability to convert waste product to a resource
6. "passive" system process
7. new capabilities not available with other technology
8. favorable environmental impact
9. less severe operating conditions (temperature and pressure)

These attributes were distributed among the commercially successful biohydrometallurgical processes as indicated in Table 1.

It is crucial here to examine in detail why these processes have been commercially successful. Beginning with copper bioleaching, it has often been reported that copper bioleaching has gained commercial favor because it is less expensive. This is undoubtedly true and succinct but such simplistic analysis does little to enlighten this analysis. Copper bioleaching's cost effectiveness is directly related to its ability to forgo much of the labor, capital, and energy costs necessary in the mine development to concentration steps in the heap, dump and in-situ leaching setting (some of these energy savings are offset by additional energy costs in the electrowinning recovery process). Furthermore, it eliminates the environmental hazards and liabilities (sulfur dioxide and arsenic laden air effluent) inherent in smelting sulfide ores.

As for gold ore oxidation, the reasons are less clear. Once again the simple answer is that it is less expensive. Unfortunately, the answer is more complex than that. First, the capital costs of such a plant are 15-35% less costly than a pressure oxidation or roasting plant (Holmes et al., 1988). Second, the operating costs, due to less severe operating conditions than the other two oxidation process alternatives, require fewer and less highly skilled operators. Furthermore, the process is not as energy intensive as the alternatives, further contributing to the lower operating costs. Finally, the biological oxidation process produces little or no air effluent (but about equal amounts of solid effluent) reducing the costs of air effluent mitigation.

The biosorption processes at this point largely have achieved their limited commercial success because of two primary attributes; (1) their ability to trap and remove

metals in very low concentrations, and (2) their ability to recycle waste metals back to industry. Of these biosorption processes, those that utilize the ability of the cell envelope or other extracellular polymers to trap metals seem to carry the greatest potential for commercial development. These polymers do not require that the system be living, avoiding the additional costs associated with maintaining a living system, while being impervious to changes in metal concentration, pH, temperature, etc., that living systems are likely to find uninhabitable.

Finally, the success that biological cyanide destruction has achieved has been a result of increasingly restrictive environmental protection regulations and the ability of this process to singularly meet these regulations where the alternatives could not. Also contributing to its success has been the relative "passivity" of the process. It requires little in the way of operating costs, requiring no continual addition of reagents, only small amounts of electricity, and relatively small amounts of labor to maintain operation.

PERCEPTIONS OF TECHNOLOGICAL SOLUTIONS BY THE INDUSTRY LEADERS

Further insights for this analysis may be gained from responses to questions regarding potential technological solutions to the industry's economic problems that were included in the survey referenced above. The mining industry CEOs were asked to identify the key characteristic of a technology that is most likely to improve their competitiveness with foreign producers. Given a wide choice of possible characteristics such as less energy intensive, lower capital costs, environmentally benign, etc., they overwhelmingly identified higher labor productivity as the most important characteristic of an effective new technology to improve their competitiveness.

Finally, these CEOs were asked to identify the technology area with the greatest potential to improve their relative competitiveness. Although they failed to reach anything resembling a consensus on this issue, it is important to examine their principal selections. Both in-situ mining and optimization and control were the first choice of 20% of the respondents, while advanced rockbreaking and intelligent mining systems were chosen by 15%. Advanced biological recovery techniques garnered first place in 12% of the surveys (over 50% of the precious metal respondents). These responses, while less unified than the responses to the previous two questions, do display some important priorities of these leaders of the industry, most particularly their emphasis upon in-situ mining and advanced rockbreaking techniques.

CONCLUSIONS

Then, through the intersection of this analysis and evidence of the economic problems and bottlenecks of the mining industry with the key attributes of biohydrometallurgical processes and the insights of the mining industry leaders, we can now draw some conclusions regarding the future of biohydrometallurgy. This intersection will unveil those biohydrometallurgical processes that have the greatest probability of reducing production costs dramatically and opening the "great new vistas" described by Mr. Noyce and defining the technology and the new industry when they settle into the "steady state" that Dr. Simon referred to.

First, the iron- and sulfur-oxidizing bacteria Thiobacillus ferrooxidans will continue to play a pivotal role in the recovery of some metals where pyrite is present. These will continue to be copper and uranium, but will also include other sulfide metal ores that contain nickel, zinc, and lead. They will reduce the cost of recovering these metals dramatically from low-grade sulfide deposits largely in-situ or heap leaching environments. Those metals and processes most energy intensive and environmentally malign are the most likely to be replaced by these processes, most particularly, the recovery of nickel.

Second, the biological processes that provide for in-situ leaching capability, yet undeveloped, will find a solid commercial market. As ore grade declines, it will become increasingly necessary to reduce the energy, labor, and capital costs associated with ore extraction. As recognized by the CEOs in our survey, in-situ mining provides the capability of reducing dramatically resource recovery costs. Biological in-situ recovery of metals, although slow, requires little capital, energy, or labor costs and is the most environmentally benign of the metal recovery processes. Furthermore, as in-situ processes produce less waste rock, the land acquisition and resulting mine development capital costs are reduced. In-situ leaching could also become critical if the Environmental Protection Agency declares this gangue rock a hazardous waste. Although the development of new strains of bacteria and processes may enhance the economics of these processes, presently the limiting technology is the lack of low-cost and effective rock fragmentation processes (Ismay et al. 1986). More in-situ leaching would be cost-effective in North America with presently available organisms if the industry had available these lower cost rock fragmentation methods. It is time now for the mining industry to begin to apply some creative thinking and research monies into new rock fragmentation processes to take full advantage of the many economic benefits of biological in-situ leaching. The most widely utilized rock fragmentation technique--blasting--has been utilized for the fragmentation of rock

since at least 2000 B.C. (Singer et al., 1968). New technology for such low-cost rock fragmentation may not need to be developed anew, but rather borrowed from other industries and adapted for the resource recovery industry. Both ultrasound and laser technology immediately come to mind, but this should not be considered an exhaustive list.

New or improved organisms for in-situ leaching may include genetically-engineered organisms but such organisms and processes are likely to have severe regulatory and scientific hurdles to overcome. The most serious of these is the competition from "wild" native strains of bacteria inhabiting the ore. These will be most acute among in-situ leaching environments where the perceived danger of environmental release of an engineered organism and the lack of an aseptic environment accentuate these regulatory and scientific drawbacks, respectively.

Third, considering the growing global awareness of the long-term impact of environmental damage and the nature of the environmental impact of operating and abandoned mining sites, as well as the increasing capability and enforcement by the EPA of private liability for environmental damage, there will be considerable cost advantages in the utilization of "passive" environmental mitigation systems. These are systems that approach or achieve homeostasis where little or no reagents or other inputs are necessary to maintain the system. All necessary energy and/or nutrients are available to the organisms. Some abandoned mine sites we now know are capable of environmental damage for a millennia or more, such as the ancient Roman lead-zinc mines in Wales (Wixson et al., 1985). If both the EPA and private lawsuits are successful in holding mining companies financially liable for these sites, the financial burden to the industry could be untenable. Instead, the industry is likely to seek a technological solution that provides for a mitigation system that can stabilize the abandoned site indefinitely with little or no operating inputs. This will be necessary due to the nature of these sites, as the costs of mitigating a hazardous or toxic effluent in perpetuity with a system with even relatively small operating costs will prove prohibitively expensive. Furthermore, both state and federal regulators are likely to require the establishment of such systems to protect against the insolvency of the company that may leave the state and taxpayers responsible for the long-term protection of the environment.

Fourth, biohydrometallurgy, in its steady state, will encompass several biosorption processes. These processes have the ability to not only remove metals from toxic effluents, but also to recycle the metals and return them to the market and industry. Biosorption processes are capable of removing

metals from very large and dilute aqueous solutions, a capability that will become increasingly important as metal concentration standards in drinking water and other waters become stricter in coming years. Although other processes exist for the removal of these metals from solution and recycling, the engineering of biosorption processes hold the greatest promise for reducing costs dramatically. Most importantly, those utilizing the cell envelope and extracellular polymers do not require a living system, which provides the capability to remove metals in varying environments where pH, temperature, metal concentration, etc. can vary and kill a living system. These biosorption polymer systems are likely to employ innovative engineering schemes that provide for durability and simple and inexpensive metal stripping from the polymer.

Furthermore, the application of organisms genetically engineered for growth rate, metal selectivity, and loading factors are likely to play a key role in biosorption, as the issues of regulation and competition with "wild" strains would be mute. The organisms could be grown in an aseptic vat and only the polymers extracted and utilized to sequester metals in an effluent stream, tailing pond, etc. While avoiding the drawbacks of genetically engineered organisms, these biosorption systems could take advantage of the profound benefits. The economics of these biosorption processes will then define the acceptable cost parameters for the primary mining of metals. As the costs of recovering metals from waste streams decline, companies may find it advantageous to "mine" various effluent streams. This will only be advantageous if these recovery costs are less than the market price. Consequently, when the price of a particular metal rises above the cost of recovering it from waste, profit seeking entrepreneurs will enter, "mine" this waste, and return these metals to the market. This increase in supply will then effectively put a ceiling on the price in these metal markets.

Finally, as the environmental mitigation costs of ore processing rises, biosorption processes are likely to be utilized as a primary mineral processing technology. For instance, metal ions in mineral process solutions may be stripped or separated from the process waters by biosorption processes. Polymers, highly selective for one metal and grown from genetically-engineered organisms, would have tremendous utility in the resource recovery industry.

VI. Environmental Impacts

As becomes clear in the case studies above biohydrometallurgy is capable and has dramatically reduced the environmental impact of the minerals industry. Most notably to date, the copper industry no longer needs to spew tons of sulfur into the atmosphere when producing copper biologically.

Instead, biologically leached copper is reduced by a process called solvent extraction and electrowinning that emits no sulfur into the atmosphere. This is only the beginning of the improved environmental impacts that biohydrometallurgy can have on the minerals industry.

Among the most exciting prospects for this emerging application of microorganisms is the ability to mine metals with a minimum of environmental disturbance. As mentioned above, current mining techniques require the removal and movement of phenomenal amounts of rock to obtain a relatively small amount of metal. When mining ceases, society is left with gaping and unsightly holes in the earth that continue to contaminate area ground and surface water, sometimes for centuries. The application of biotechnology to the extraction of metals opens the possibility of leaving the surrounding environment relatively undisturbed while removing the desired metals, in other words in-situ mining.

The concept is an intriguing one. When an ore body is identified, normally the overburden is stripped off to gain access to the ore. This overburden contains trees, plants, topsoil and other requisites of a healthy natural environment that are sacrificed for these precious and industrial metals. Once the overburden is stripped off, then the removal and movement of the vast amounts of rock begins. The rock, too low in concentration of metals to be economically viable to process using conventional technology, is then disposed of in nearby areas by creating mini-mountains of waste with environmental degradation problems of respective scale. With biotechnology, the possibility exists that such metals would be removed with little environmental disturbance. Once an ore body has been identified and deemed economic to develop, wells would be drilled into the ore body and the ore fractured. Then the ore body would be inoculated with the specific bacteria for that specific ore and flooded with water. Either by batch method or in a continuous process, this water would be collected or pumped to the surface pregnant with the desired metals. The only lasting impact on the site beyond the completion of mining would be several capped holes in the earth. The surface of the mine would otherwise show little degradation either environmentally or aesthetically, and inside the ore deposit would remain intact minus a small fraction of valuable metal.

Homestake Mining has developed a biological means of degrading cyanide from its waste waters. Cyanide is used at virtually every gold and many silver mining operations throughout the world. This chemical, toxic to nearly every form of life, is used for its unique ability to chemically

bind with these precious metals therefore inexpensively removing the metal from heap leaches. This chemical is then contained in huge containment ponds where it is held until it naturally degrades in sunlight. Unfortunately, all too often these containment ponds accidentally release cyanide into the environment where the effect can be devastating to life downstream. The Homestake process is capable of degrading the cyanide into its innocuous components, carbon and nitrogen, where it can then be released to the environment without toxic effects.

Among the areas of biohydrometallurgy gaining considerable attention in recent years is the desulfurization of coal. Coal is a relatively heterogeneous substance, so every coal is slightly different from the next, but all coal has some component of sulfur. This sulfur when burned combines with the oxygen necessary for combustion forming sulfur dioxide, the precursor of acid rain. This sulfur is primarily found in two forms, inorganic in a compound with iron (pyrite), and organic, where it is bound to the coal molecule. As noted above, Thiobacillus ferrooxidans is very effective at oxidizing sulfide-metal compounds. This property has been effectively utilized to remove this inorganic compound from coal. Additional research is being conducted at numerous laboratories to remove the organic component, but this is proving much more difficult because it is bound in the coal molecule and the heterogeneous nature of coal (if you find a way to remove the organic sulfur from one coal, it may not necessarily apply to the second coal). In the near future, America's electric industry may be able to burn our most abundant fossil fuel without regard to the sulfur dioxide emissions if this continuing research proves successful.

The ability of some microorganisms to adsorb metals in aqueous solutions--biosorption--could play a critical role in removing metal ions from contaminated waters. Although other metal removal methods exist, the ability of biosorption to remove metals from very dilute solutions is unique. Furthermore, by returning these metals to industry, this process will reduce the need for additional environmentally degrading mining activities.

The "ecological engineering" of using swamplands, algae, fungi, and sulfate reducing bacteria in today's active and inactive mines may produce the mine sites of the 21st century. Such swamplands concentrate metals by the sulfate reduction process of microorganisms, the adsorption to the surface of fungi, algae, and higher plants, and the absorption of metals into the microorganisms and plants. As these organisms die and decay, the concentration of metals in these swamplands is likely to become high enough eventually to become economically attractive to "mine." Such a swampland would likely be

biologically leached by the introduction of Thiobacillus ferrooxidans or other oxidizing micro-organism. Even after many years of metal concentration in the sediments of the swampland, it would be unlikely that concentrations would exceed the threshold for conventional mining. In such a case, metal production would become an entirely biological process with little active human participation and minimal exogenous energy input (actually, the oxidation of sulfide minerals by bacteria is an exothermic reaction. Such areas are "hot" from the energy release as evidenced by the melting of snow from these ores on frigid days). The naturally occurring Thiobacillus or other organism would be oxidizing the sulfide mineral placing metal ions in an acidic aqueous solution. Then the swampland would intercept the outflow from the inactive mine and concentrate these metals by a constructed swampland. After many years of continual metal concentration, the sediment at the bottom of the swampland would contain metal concentrations that would exceed the economic threshold for viable biological mining. The water outflow from the original inactive mine would be diverted around the first swampland into a fresh swampland ready for concentration. The first swampland would then be leached by thiobacillus. Replacing the solvent extraction segment of current processing would likely be a supersensitive biosorption filter constructed of dead microorganisms with extraordinary ability to attach to metals would remove the metal from the pregnant leached solution (several such "filters" have been developed and have been used commercially, principally on industrial wastewater). This would complete an entire cycle of metal production entirely done biologically with little energy input and little human enterprise.

VII. Public Policy

In President Bush's 1988 presidential campaign speeches he vowed to seek means to reduce the production of waste and encourage recycling. He has gone so far as to propose a tax on virgin materials to improve the relative production economics of recycling and reduction in the production of

waste. The metal mining industry is a prime example of where private self-interest has led an industry to adopt techniques that achieve both of these goals-- production efficiency and improved environmental compatibility, when public policy has been properly applied to give the industry flexibility in achieving environmental mandates reflecting the public's environmental concerns. Although this process is likely to continue slowly, stimulated by private self-interest, the metal mining industry and its antecedents continue to be responsible for the creation of billions of tons of waste, spew tons of sulfur into the atmosphere, and acidify the nation's water and contaminate them with metals. What makes this opportunity unique for American industry is the opportunity to serve these often conflicting goals of industrial society simultaneously: productive efficiency and a safe and clean environment.

It should be noted here that the adoption of biotechnology by the mining industry did not come about in an unregulated, totally free market environment. The environmental regulation of the 1960's and 70's saddled the industry with a greater share of the economic diseconomies (diseconomies are costs or benefits that accrue from an activity but are not attributed to the private entity responsible) of their mining activities. As they were forced to absorb more and more of these diseconomies by reducing their contamination of local surface and ground water and reducing their sulfur dioxide effluent, their conventional technology--now some 6500 years old-- was no longer practical. Without this regulation, it is unlikely that the industry would now be beginning its long trek toward post-industrial techniques.

The Bush Administration needs to step forward now with a commitment and partnership between industry, academia, and government to continue research and development of these technologies (the 1988 Office of Technology Assessment report on the copper industry makes similar recommendation). The U.S. metal and mining industry spends little on research and development--less than 2% of sales versus 3.5% for U.S. industry overall in general and almost nonexistent amounts on biological processes (Newmont Mining recently proved to be among the most farsighted as they established a Biological Metallurgy Lab in Salt Lake City lead by the venerable microbiologist, James Brierley. Among his many contributions to the field of Dr. Brierley, he was the first to isolate and culture an organism that oxidizes sulfide minerals at very high temperatures that he found in a hot geyser pool in Yellowstone National Park and it now carries his name, Sulfolobus brierleyi). The initiative for such a consortium should come from the Federal government. This might smack of "industrial policy" by some and therefore deemed politically repugnant, but a quote from Nashiro Amaya, former vice-

minister of Japan's Ministry of International Trade and Industry (MITI) may shed some light on the matter:

Businessmen are risk-averse. Therefore, if the invisible hand cannot drive the enterprise to R & D, the visible hand must.

The unregulated free market is a magnificently efficient machine. Unfortunately, the machine maximizes short term cash flows and profits, most acutely when the future is very uncertain. To move the American minerals industry forward into efficient, environmentally compatible metal production, will require that entity whose very existence is justified by the convergence of all interests in the nation into a single "national interest", that is the Federal government. The Department of the Interior, with responsibility for the nation's national park's and the overseer of the U.S. Bureau of Mines should form a new agency responsible for oversight and guiding this function. This agency would assist research at universities and in the private sector but also catalyze the formation of a research consortium among the mining companies. Such a consortium would spread the risks and rewards of research and development so that no one company need take such risks alone. The result would be an industry with lower costs and a gentler, kinder impact on the environment.

It is critical that public policy and regulation must also be reviewed regarding the application and utilization of genetically engineered organisms in this field. Currently, guidelines have been developed that apply to what have now become the traditional fields of genetic engineering--that is agriculture, pharmaceuticals, and medicine--but such guidelines fail to account for the unique aspects of these organisms and this application. Most important in distinguishing these organisms from those used in the medical, pharmaceutical, and agricultural biotechnology industries is that these organisms do not inhabit or otherwise derive food or energy from living or formerly living organisms. They organisms are chemolithotrophs-- they derive their energy from chemical sources. Consequently, the risk of their becoming a pathogen to human beings, plants, or animals--the ultimate fear and nightmare of the public regarding genetic engineering--is very low. Consequently, the risks of associated with the environmental release of such an organism is likely to be several orders of magnitude smaller. Present regulations fail to account for this key distinction. Researchers worry, in fact, more about the diametrically opposed problem. They are concerned that the organism will be

unable to survive in competition with wild strains. The organism, like a rose in an untended patch of weeds, will be overcome by competition with organisms that have over millions of years evolved gene pools optimal to exploit that ecological niche. As a result, such safeguards as apply to organisms used in the pharmaceutical and agricultural industries need to be reviewed for their applicability to this field.

The Bush Administration should follow through on its campaign pledge to institute a virgin materials tax. The long-term benefits to the U.S. economy and global environment could be considerable if the right tax is applied. Such a tax would discourage the use of virgin (new) materials extracted from the natural environment and encourage the recycling of materials. The end result would be a lessened impact upon upon the natural environment as production from recycled sources would increase and virgin sources increase with the increased financial incentive. With regards to biohydrometallurgy, such a virgin materials tax would provide the minerals industry a financial incentive to adopt and develop biological means of mineral production. Presently, the greatest use of biohydrometallurgy is in leaching of copper waste dumps. Such activity would be further encouraged by the virgin materials tax as would such processes as biosorption that is capable of removing metals from very dilute aqueous solutions and recycling them.

Finally, the mining industry needs engineers and scientists trained in this field. Mining engineers are educated in chemistry, physics and the various engineering dynamics but few are trained in biology. The nation's mining schools need to initiate this critical component into their training of tomorrow's mining engineers if these processes are to be adopted and properly engineered.

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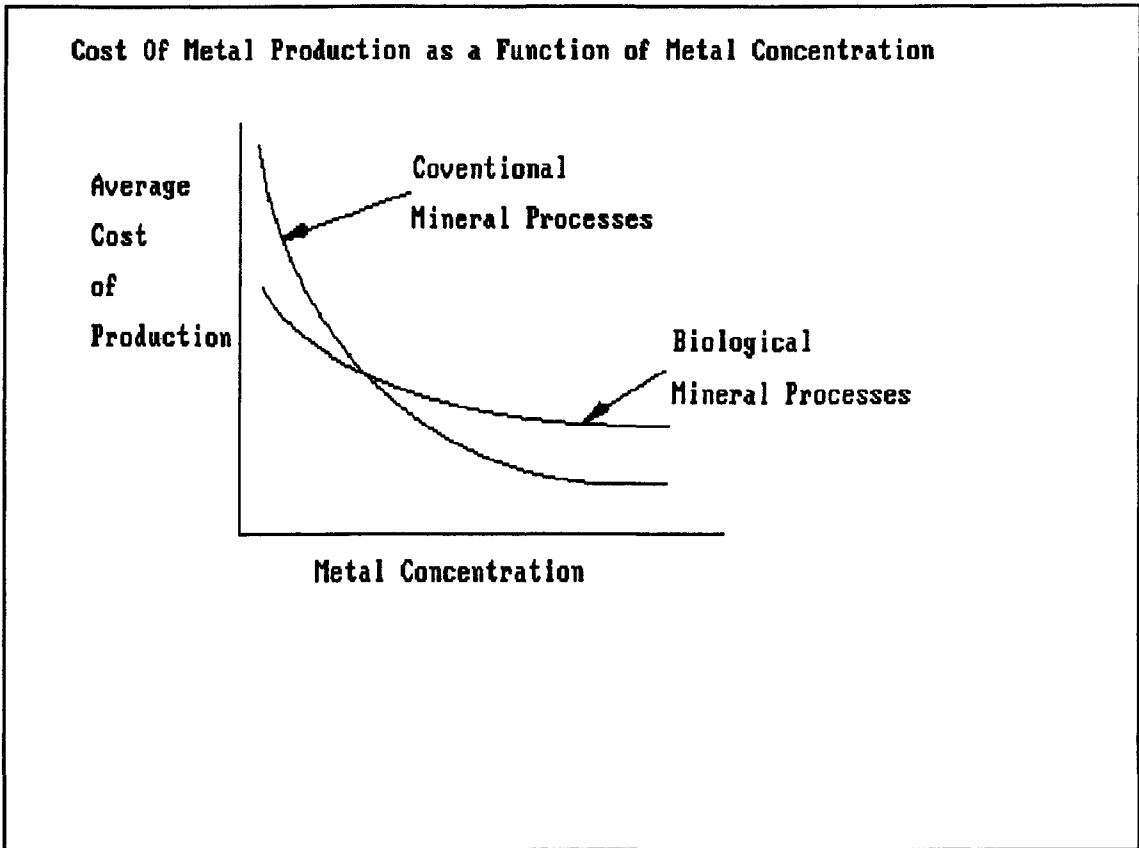


Figure 2

Table 1

Process Economics

	In-situ Capabilities	Lower Energy Costs	Lower Capital Costs	Lower Labor Costs	Convert Waste to Resource	Passive System	New Capabil.	Favorable Environ. Impact	Less Severe Op.Conditions
Copper Leaching	X	X	X	X	X			X	
Gold Ore Oxidation		X	X	X				X	X
Biosorption		X			X		X	X	
Cyanide Destruction		X		X		X		X	