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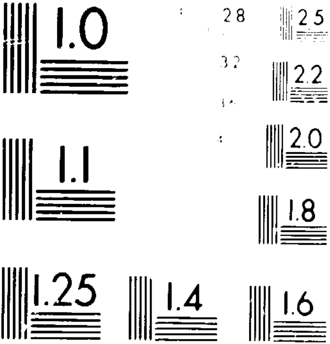


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# THE APPLICATION OF BIOTECHNOLOGY IN DEVELOPING COUNTRIES: THE CASE OF MINERAL LEACHING WITH PARTICULAR REFERENCE TO THE ANDEAN PACT COPPER PROJECT*

by

Alyson C. Warhurst**

1911

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** Researcher, SPRU, the University of Sussex, United Kingdom.

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ABSTRACT

Emerging environmental and economic trends are combining to create a new technological context within which planned mineral projects will be developed and existing ones will have to adapt to remain viable. This is increasing the complexity and number of process routes available for mining and metal recovery. With the increasing necessity to recover marginal ore, by-products and pollutant elements, these process routes will be more closely determined by the geological specifications of each mine.

Bacterial leaching can broaden this range of process routes through traditional dump leaching of mine waste, the leaching of marginal sulphide ore and concentrates in optimized systems and the resolution of certain problems in sulphide metallurgy. With the exception of concentrate treatment these are processes for which, as yet, no viable alternatives exist.

The leaching bacteria are essentially oxidation agents that attack sulphide minerals, both directly and indirectly through the accelerated creation of a ferric acid lixiviant, dissolving their mineral content and freeing the associated metal ions for recovery.

The potential of bacterial leaching is rooted in the fact that these living organisms require the fulfillment of special conditions for maximum growth and thus maximum oxidation and leaching rates. The natural (e.g. geological) characteristics of the leach system will also affect the efficiency of the biological and chemical reactions. It is here that the scope lies for optimizing the leaching process for economic gain.

This has important implications for developing countries since they have long mining histories, and thus mineral-rich dumps; and the majority of sulphide deposits and new mineral projects are within their boundaries. Virtually all the examples of commercial bacterial leaching operations - mainly in the industrialized countries - are suboptimal dump systems of waste previously considered uneconomic for metal recovery. They are suboptimal

because the microbiological component of the leaching process was not realized at the time of their construction. This means that the developed countries are limited as a source of know-how for the development of bacterial leaching in developing countries.

Furthermore, technology development in bacterial leaching puts special demands on developing-country mineral producers. Linking biotechnology with the minerals industry requires a wide range of knowledge, skill and technical inputs which involves microbiology, geology, mining, metallurgy and chemical engineering. These inputs need to be combined in multidisciplinary teams which work in close proximity to the production sector. In addition, a preliminary step to optimizing the leaching process is using indigenous bacteria and local mine water. Knowledge about the specific geological and environmental constraints on technological development is also essential.

A technology policy response is thus considered imperative if developing countries plan to apply bacterial leaching technology.

In this context the present paper develops a scheme which categorizes the requirements considered fundamental to the development and implementation of a technically and economically efficient bacterial leaching project. A subregional technology development project in bacterial leaching, the Andean Pact Copper Project, is analysed according to this scheme and the limiting and stimulating factors influencing the building up of the necessary capabilities in this area are identified. Policy suggestions are then made at the project level, drawing on this analysis, the scheme itself and literature reviews.

It is concluded that the potential bacterial leaching offers to developing countries is both promising and positive. Thus, some recommendations are made regarding areas where more general work is needed to complement project policy if the benefits of optimized bacterial leaching are to be harnessed to contribute to the development of the minerals sector of developing countries.

# PREFACE

The present paper explores the potential for developing countries of the application of biotechnology in the minerals industry; in particular, it focuses on the bacterial leaching of copper ores.

The research has been carried out from the perspective of technology policy for technical change and innovation in the area of the minerals industry. The Andean Pact Copper Project, a technology development project at the Board of the Cartagena Agreement (JUNAC), commonly known as the Andean Pact, was used as a case study.

The relevance of the Andean Pact Copper Project lies in the lessons that can be extracted from ten years' experience of technology development in the area of bacterial leaching. Its importance derives from the observation that technical changes in the minerals industry, in response to various economic and environmental trends along with foreseeable advances in biotechnology, indicate that bacterial leaching will play an important role in broadening the range of process routes available for the development of new mineral projects.

The approach adopted by this research is interdisciplinary. In part it was stimulated by the fact that as yet there exists no body of literature which examines the changing technological context in which new mineral projects will develop and existing ones will have to adapt to remain economically viable. This lacuna has important consequences for developing countries since they account for over 70 per cent of world mineral exports and over 60 per cent of planned investment in new mineral development projects; furthermore, the geological evidence indicates the existence of many more mineral deposits within their boundaries.

Although the technical literature on the minerals industry reports on the latest technical developments and new mineral projects, it fails to draw out their implications for developing countries. The literature relating directly to developing-country mineral producers is confined to economic investigations of the conditions of foreign investment by transnational mining companies or the marketing of minerals. Similarly, in the area of intercountry co-operation, the emphasis has been predominantly on marketing policies; improving prices by cartel action, for example, through joint producer organizations like the International Bauxite Producers Association (IBPA), the International Council of Copper Exporting Countries (CIPEC), or the International Tin Council (ITC).

The biotechnology literature also has failed to explore the relevance of advances in its field for the mineral industry. Although some researchers have mentioned mineral leaching as a possible area of application, it is rarely discussed further. Rather than the implications of its development being drawn out, reference is made only to a few theoretical microbiological works on the subject. Indeed, many working definitions of biotecnnology exclude bacterial leaching and the natural resource industries by referring only to the manufacturing and service sectors. Finally, the technology policy literature itself has dealt predominantly with the manufacturing and capital goods sectors of developing countries. Very little technology policy research has been carried out on the mining and mineral processing industries; nor have the special conditions of the natural resource industries been acknowledged; that is, the specificity of their geological base and the implications for local technology development.

Although this paper is by no means an exhaustive survey, an important objective is to map out the links between mining and mineral processing technology, minerals policy, biotechnology and technology policy; and to show their relevance for the development of the minerals sector of developing countries. Thus, the paper analyses technical change in the international minerals industry and its implications for developing countries; locates biotechnology and the potential role of bacterial leaching within this context; and, on the basis of detailed case-study research, draws out some policy guidelines for technology development in this area.

From the beginning, an overwhelming necessity emerged both to build up detailed technical knowledge about the mining and metal production process and to carry out field-work at the mine site. Vists to mines, and mineral dumps and informal discussions with miners, geologists, engineers and mine management proved to be a fundamental source of information for the research. It should not be forgotten that people as well as plant, equipment and rocks are also subject for investigation in dealing with technology policy for technical change. Indeed, if one has visited the mines of the Andean region one could never forget the men, women and children there and the impoverished conditions in which they live and work.

Technology policy for the mining industry in developing countries cannot be divorced from its social context and the urgency for real social development. This at least was one of the lessons which clearly emerged from field-work in Bolivia, Peru and Chile.

For these reasons the paper is a product of the following: extensive field-work in the Andean region which included over twenty mine-site visits and interviews with people at the mines, company headquarters, R and D institutes, universities and ministries; a detailed review of the technical literature; visits to centres of expertise and interviews with international experts; and an analysis of technology policy literature.

The empirical part of this research was carried out throughout 1982 based at the offices of the Technology Policy Group of the Andean Pact and without their generous support and kind assistance, this work could never have been completed. The field-work was supported by the Technology Programme of UNIDO. Generous and crucial support was also provided by the Science Policy Research Unit at the University of Sussex, United Kingdom. Many other institutions and companies were very helpful during the field-work, particularly through providing transport and access to mines and research facilities. Principal amongst these were: Instituto de Investigación de Minería y Metalurgia (IIMM), Corporación Minera de Bolivia (COMIBOL) in Bolivia; Centro de Investigación Minera y Metalurgica (CIMM), Corporación Nacional del Cobre de Chile (CODELCO); Disputada (subsidiary of Exxon in Chile), Instituto de Investigaciones Tecnológicas (INTEC), the University of Chile in Santiago, and the Catholic University of Valparaiso in Chile; Empresa Minera del Centro del Perú (CENTROMIN), the national mining corporation of Peru (MINERO-PERU) and Instituto de Investigación de Geología, Minería y Metalurgia (INGEMMET) in Peru. Finally, I should like to thank the following people personally for their invaluable help and support: Liliana Acero, Fernando Acevedo, Carlos Aguirre, Catherine Aliende, Giselle Argenti, Jorge Banach, Fabrizio Bargellini, Martin Bell, Julio Bonelli, A. Bruynesteyn, M. Burcher, Saúl Cabrera, Vicente Cárdenas, Narciso Cardozo, Norman Clark, Auriel Corimaya, Adam Daum, M. Dizy, Cristina Echevarría, Carlos Feriz, Juan Fernández, Gustavo Flores Guevara, P.M.J. Gray, I. Herbert, César Herrera, Mary Herrera, Kurt Hoffman, Gilberto Hurtado, Jeannete Ivazeta, J. Jacobi, G. Janka, Rolando Jordan, Raphie Kaplinsky, A. Lenel, Eleuterio León, César Loayza, Antonio Luraschi, William Macha, Humberto Mallo, Marcelo Marti, Carlos Molina, Waldo Neves, José Norman, Geoff Oldham, Mario Paulsen, Jurgen Picardo, Angel Pinaya, W. Pincheira, Salomón Rivas, Jorge Rodríguez, Diógenes Roques, N.W. de la Roux, Francisco Sagasti, Mario Salari, Teresa Salazar, Bernardette Silva de Enríquez, Ruth Silva de Enríquez, K. Singh, Claudia Solero, Lucho Soltau, Luis Soto-Krebs, M. Tributch, Alvaro Ugalde, Toya Uribe, Jaime Urquidi, Miguel Vargas, Juan Zegarra.

## ABBREVIATIONS

| | |
|---|---|
| AIME | American Institute of Mining, Metallurgical and Petroleum Engineers, United States of America |
| BC Research | British Columbia Research Council, Canada |
| CENTROMIN | Empresa Minera del Centro del Perú (the mining company of central Peru, formerly the Cerro de Pasco Corporation) |
| CIMM | Centro de Investigación Minera y Metalurgica (centre for mining and metallurgy research), Chile |
| CIPEC | Intergovernmental Council of Copper Exporting Countries, France |
| CODELCO | Corporación Nacional del Cobre de Chile (national copper corporation of Chile) |
| COMIBOL | Corporación Minera de Bolivia (mining corporation of Bolivia) |
| ENAF | Empresa Nacional de Fundiciones, Bolivia (national smelter and refinery of Bolivia) |
| GTZ | German Agency for Technical Cooperation (Deutsche Gesellschaft für Technische Zusammenarbeit), Federal Republic of Germany |
| IBPA | International Bauxite Producers Association |
| IDRC | International Development Research Centre, Canada |
| IIMM | Instituto de Investigación de Minería y Metalurgia (research institute of mining and metallurgy), Bolivia |
| IMM | Institution of Mining and Metallurgy, United Kingdom |
| INCITEMI | Instituto de Investigación de Ciencia y Tecnología para la Minería, Peru |
| INGEMMET | Instituto de Investigación de Geología, Minería y Metalurgia (institute for geological, mining and metallurgical research), Lima, Peru |
| INTEC | Instituto de Investigaciones Tecnológicas, Chile |
| IPT | Instituto de Pesquisas Tecnológicas (institute of technological research), Brazil |

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|---|---|
| ITC | International Tin Council, United Kingdom |
| JUNAC | Junta del Acuerdo de Cartagena (Board of the Cartagena Agreement) |
| MINERO-PERU | national mining corporation of Peru. |
| OAS | Organization of American States, United States |
| TNO | Central Organization for Applied Scientific Research in the Netherlands (Toegepast Natuurwetenschappelijk Onderzoek) |
| UNEP | United Nations Environment Programme |

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|---|---|
| DNA | deoxyribonucleic acid |
| PVC | polyvinylchloride |
| R and D | research and development |

CONTENTS

## Figures



## Tables

## INTRODUCTION

Certain biological agents, principally microorganisms, have the capacity to contribute to the conversion of raw materials into useful products. Biotechnology is the term generally used to describe the application of these biological reactions to industrial processes.

For several centuries societies have been producing fermented foods and beverages and recovering metals from bacterially-activated mine waters. These activities were usually carried out without knowledge of the causative agents. However, it is the understanding of the biological and chemical mechanisms at work which distinguishes modern biotechnology since this is the first step towards optimizing their efficiency for economic gain.

The productivity of microorganisms and the efficiency of related biological reactions - which may determine the economic competitiveness of an industrial process - can now be improved by an increasing number of techniques. For example, particular nutrients may be added to the system, specific environmental parameters changed, strain selection and improvement carried out and genetic engineering undertaken.

Previously the applications of biotechnology were constrained by the necessity to use biological agents which carried out the required conversion processes naturally. However, genetic engineering, using recombinant DNA technology, is rapidly opening up the way for the significant alteration of the properties of existing strains of microorganisms as well as novel products and processes. By manipulating the DNA - the genetic material of cells which directs their metabolism - it is possible to implant "instructions" which can modify the cells' behaviour to benefit industrial processes.

Indeed it is the growing number of industrial processes to which biotechnology can now be applied which makes it an area of considerable current interest. It is now possible to categorize at least seven major sets of application of biotechnology to industry. These are: energy production, food production, agriculture inputs, feedstocks for the chemical industry, environmental management, medical products and resources recovery.

This paper will focus on the latter category of applications. Its objective is to evaluate the application of biotechnology to mineral extraction and metal recovery, particularly copper, and to assess the implications of advances in this area for mineral-producing developing countries. This is done from both a technical and technology policy perspective using the Andean Pact Copper Project as a case study.

The Andean Pact Copper Project was chosen as a case study since it represents one of the few examples of the development and application of bacterial leaching technology in developing countries. It is particularly interesting since it was designed to achieve specific technology policy objectives. These included the development of local resources and skills and a more efficient system of technology transfer both from developed countries and between developing countries. Hence, an analysis of this project, apart from its intrinsic interest as a policy endeavour in the area of biotechnology and the mining industry, provides a useful source of guidelines and ideas for other developing countries considering exploiting the potential of bacterial leaching.

The recent awareness within some industrial sectors of the potential of biotechnology can be attributed not only to academic advances made by microbiologists and geneticists, but also to the incentives for innovation provided during the 1970s and early 1980s by economic and environmental considerations such as the depletion of natural resources, chemical pollution and rising energy costs.

In the case of the minerals industry, technical developments over the last decade in response to these factors mean that there now exist a number of technically viable options to be considered during process route selection. Recent innovations in pyrometallurgy include: matte-making processes such as flash furnaces, oxygen sprinkling smelters and electric furnace smelting, and continuous matte-making and converting techniques like the Noranda and Mitsubishi processes. In the area of hydrometallurgy, processes for leaching sulphide minerals and mixed ores using chloride, cyanide, ammoniacal and bacterially-activated solutions have been developed; and solvent extraction combined with electrowinning is emerging as an important economic alternative for metal recovery.

A unique characteristic of the minerals industry is that the geological peculiarities and geographical location of each mine site mean that each is a special case requiring a specially designed process route rather than one to meet more general requirements. So, in the present international climate, planners of new mineral projects have to consider a wider range of process routes, which may even include unconventional alternatives, so that the treatment showing the best overall economics can be found.

It is in this mutual sphere of biotechnological advance and economic and environmental pressures for technical change in the minerals industry that the potential of bacterial leaching is located.

Bacterial leaching is a naturally occurring process whereby certain microorganisms, notably Thiobacillus ferrooxidans (T. ferrooxidans), facilitate the conversion of normally insoluble sulphide minerals, such as pyrite, chalcopyrite etc., into water-soluble forms, thus freeing the associated metal ions for subsequent recovery. The bacteria obtain the energy they need for functioning and growth from the oxidation of inorganic compounds of iron and sulphur and in doing so accelerate their oxidation to sulphuric acid and ferric sulphate solutions up to $10^6$ (a million) times faster than would normally occur in the presence of air alone. This in turn significantly speeds up the dissolution of water-soluble sulphide minerals. In addition, there is reliable evidence to suggest that several bacteria strains (see section 1.3.1.3 below) directly attack the oxidizable parts of normally water-insoluble sulphide minerals, transforming and breaking them up into water-soluble forms.

Since bacteria are living organisms, they require special conditions for maximum functioning and growth and thus optimum oxidation and leaching rates. In general they require abundant oxygen, a highly acid pH, specific nutrients and a moderate temperature while some dissolved metals, for instance uranium, can be toxic to certain strains. However, there are precise conditions which enable optimum bacterial activity and these are generally best fulfilled for each bacteria strain by its indigenous environment.

Similarly, the characteristics of the leach system - its mineralogy, particle size, dump porosity, air updraught, temperature profile etc. - will also affect the efficiency of the biological reactions and thus the amount of, and rate at which the contained metal can be taken into solution.

It is these wide-ranging sets of parameters which provide the scope for optimizing the bacterial leaching process for economic gain. Three main routes to optimization are identified and discussed in this paper. These are: leach system design, solution management and improvements of the bacteria. Indeed, genetic engineering offers great potential for improving leaching bacteria. For example, cell adjustments could be made so that the bacteria selectively leach particular sulphide minerals, or are unaffected by certain toxic substances; and the oxidation reactions themselves could be speeded up.

However, the precise biochemical mechanisms at work, and indeed the detailed characteristics of the bacteria themselves, are still inadequately understood. Nor has it been reported that genetic engineering has been successfully carried out on these species.

This, coupled with a corresponding lack of knowledge about the nature and extent of mineral reserves to which the process can be applied, means that at this stage it is impossible to determine with accuracy the economic impact that bacterial leaching may have on the minerals industry. However, this does not prohibit a detailed exploration of the potential of bacterial leaching in the present paper. Indeed, the indications are that in the light of the economic and environmental trends identified, bacterial leaching can provide an important means to expand mine capacity at low marginal cost; while, at the same time, reducing pollutant effects and stimulating wide-ranging, economically significant internal capability accumulation processes.

It is argued in the present paper that bacterial leaching may contribute to broadening the range of possible process routes for mineral extraction and metal recovery in three main ways.

First, the leaching of sulphide values from waste dumps of previous mining operations, which worked with a higher cut-off grade, or the "flushing out" of old mines, using <u>in situ</u> leaching techniques. Thus recuperating "extra" mineral content and, in so doing, preventing natural pollution by uncontrolled acidic effluents.

Secondly, the leaching of overburden from newly-developed mineral deposits, and of marginal ore during ongoing operations, in heaps specifically designed to optimize the leaching process for short-term economic gain.

Thirdly, the more novel possibility of leaching sulphide concentrates in vat or confined systems under carefully controlled conditions.

These elements have important implications for mineral-producing developing countries, not least with respect to technical choice and decision making, since the majority of sulphide mineral deposits and planned sulphide mine development projects are located within their boundaries. Furthermore, those countries have long mining histories, which would imply that significant mineral wealth is contained in existing dumps.

However, virtually all the examples of the commercial applications of this technology are in dumps of what was previously considered waste or marginal ore and are mainly located in the industrialized countries (for example, south-west United States of America, Canada and the Union of Soviet Socialist Republics). Since it was realized only recently that sulphide leaching has a microbiological component, these dumps were not constructed according to parameters to optimize the process. So although these bacterial leaching operations account for over 10 per cent of the production of copper in the United States, they generally have recuperation rates of between 60 per cent and 40 per cent of the contained metal in a period which usually extends between five and twenty years. Laboratory and pilot plant projects have indicated that recuperation rates of over 80 per cent can be obtained from optimized leach systems in periods as short as 18 months to two years. Such results were obtained by CENTROMIN, Peru, at its Toromocho mine during the Andean Pact Copper Project.

The principal implication of all this is that there is no precedent in the industrialized countries of optimized bacterial leaching operations. There are no general models upon which the developing countries can design their leaching projects; and, as a source of technological know-how in this field, the potential of the industrialized countries, although important, is limited.

In addition, linking biotechnology with the minerals industry demands a combination of a wide range of knowledge, skill and technical inputs and there are very few examples of multidisciplinary teams in the traditionally division- and department-structured mining companies.

In this context, based on a detailed literature survey, discussions with experts and field-work at the mine sites, a scheme is developed (in section 1.5), setting out the categories of technological capabilities required for the development of an economically and technically efficient bacterial leaching project. This technological capabilities "framework" forms the core of the research. It provides the basis for both the critical analysis of the Andean Pact Copper Project and the guidelines for the related technology policy proposed in the concluding chapter.

The paper organizes the findings of detailed field-work and literature searches in both Latin America and the United Kingdom in the following way: Chapter I examines the potential of bacterial leaching in the context of technical change in the minerals industry and the copper production process. Subsections treat, in turn, the copper production process and current trends in its development; the implications of these trends for developing countries and the potential of bacterial leaching technology; the mechanism of bacterial leaching; leach system design and optimization; and, finally, a scheme for the technological capabilities required for bacterial leaching technology development.

Chapter II summarizes the arguments developed in chapter I. Lessons are extracted from the analysis of the Andean Pact Copper Project and, based on the Bacterial Leaching Technology Development Scheme of chapter I referred to above, some guidelines are discussed for future projects. Finally, some tecommendations are made relating to possible policy responses, at a more general level, to the potential offered by bacterial leaching to developing countries within the changing technological context of their mineral development.

The analyses which follow of both the potential of bacterial leaching technology and its application within the Andean region, illuminate several currently topical technology policy issues. Perhaps the most interesting and important of these is the observed tendency inherent within the development of bacterial leaching technology which leads to the localization of the technical change process. This is because of the intrinsic necessity for local capability accumulation and utilization if an optimally operating leach system is desired.

There are two principal reasons for this: first, the essential input which site-specific mining, mineralogical and metallurgical knowledge forms during the design, implementation and operation of bacterial leaching projects. Secondly, the unreliability and impracticality of trying to develop parameters to optimize the environment-sensitive activity of the leaching bacteria outside of the production sector and away from the intended site of application.

Overall, although accepting that bacterial leaching will not be appropriate in every case, what clearly emerges from this work is that the potential for applying biotechnolgy to the minerals industry of developing countries is both promising and positive. Further study, however, is needed with respect to policy for both maximizing the benefits and optimizing the local participation. It is hoped that the present paper contributes in some way to the provision of guidelines to achieve these ends.

# CHAPTER I

## THE COPPER PRODUCTION PROCESS, TECHNICAL CHANGE AND BACTERIAL LEACHING

Throughout this paper the bacterial leaching of copper minerals will be considered in the overall context of the copper production process. This is because, in any particular process route of metal extraction, bacterial leaching will constitute only one of a number of interrelated stages.

In this chapter, bacterial leaching and the factors affecting its industrial application are discussed under the following headings: the copper production process and current trends in its development; the potential of bacterial leaching for the copper-producing developing countries, the mechanism of bacterial leaching; and leach system design and optimization.

Finally, an analytical technological capabilities framework is developed for assessing the requirements for technology development in the area of bacterial leaching.

The information reviewed in this chapter will also provide essential background material for analysing the Andean Pact Copper Project, and will indicate the basic factors which require consideration in bacterial leaching operations and the preliminary stages of related policymaking.

### 1.1 The copper production process and current trends in its development

#### 1.1.1 Geology of ore deposits

The copper production process is essentially related to the geological nature of the ores to be mined. Ores, or reserves, are mineral deposits where the metal-bearing minerals are sufficiently concentrated to be economically extracted given current mining and processing costs and metal prices.

The types of copper deposits, and their grades, tonnages and mineral compositions are a function of particular ore-forming geological processes. It is these, along with economic and social factors, which determine costs of production, process route specifications, nature and sophistication of technology, labour requirements and levels of expertise.

Copper-bearing minerals are divided into two main groups according to chemical composition. The sulphide group constitutes 90 per cent of known copper reserves, and the oxide group the remaining 10 per cent. Copper mineral deposits are classified according to three main types - porphyry, stratabound and massive sulphide. They constitute roughly 50-55 per cent, 30-35 per cent and 10 per cent respectively of the world's total mined copper (about 8 m cubic tons). 1/

(1) Porphyry deposits

These form huge discontinuous belts of disseminated mineralization and are usually composed of sulphides like pyrite, chalcopyrite, covellite, bornite, arsenopyrite and molybdenite in an igneous host rock. Most have gradational boundaries so that the zones surrounding them are sub-economic or "protore". Protore may become ore if the price of metal increases or if technical change reduces the cost of extraction enough to make mining and recovery economically viable. This may be one consequence of the application, and optimization of bacterial leaching technology to marginal ore. Furthermore, what constitutes recoverable copper may depend in part upon the by-products associated with it in the ore body. Porphyries are commonly associated with gold, silver, molybdenum and nickel. Similarly, a copper deposit may be considered unviable if it is "dirty", i.e. if it is associated with pollutant minerals like arsenopyrite and bismuth which either give off pollutant gases or require expensive inputs of chemicals to neutralize them at the smelting stage. The importance of these points will become clearer in the discussion of bacterial leaching, since this process is most commonly applied to complex sulphides from porphyry deposits which are too low grade or dirty to be treated by conventional concentrating and smelting methods.

The grades and tonnages of copper porphyry deposits vary. In the main, porphyry deposits typically contain: 1-2 per cent copper in 500-1,000 metric tons of ore, in Peru and Chile; 0.4-0.8 per cent copper in 200-500 m tons of ore, in south-west United States of America and Mexico; and 0.3-0.5 per cent copper in 50-200 m tons of ore, in Papua New Guinea and Canada.

(2) Stratabound deposits

These differ from porphyry deposits in being smaller (1-100 m tons of ore), of higher grade, and in having fixed boundaries. This means that there may be smaller tonnages of marginal ore available for bacterial leaching. Most are located in Zambia, where they contain 2-4 per cent copper in sulphide form, and in Zaire, where they contain 4-6 per cent copper mainly in oxide form. Cobalt is the economically important by-product associated with such deposits.

(3) Massive sulphides

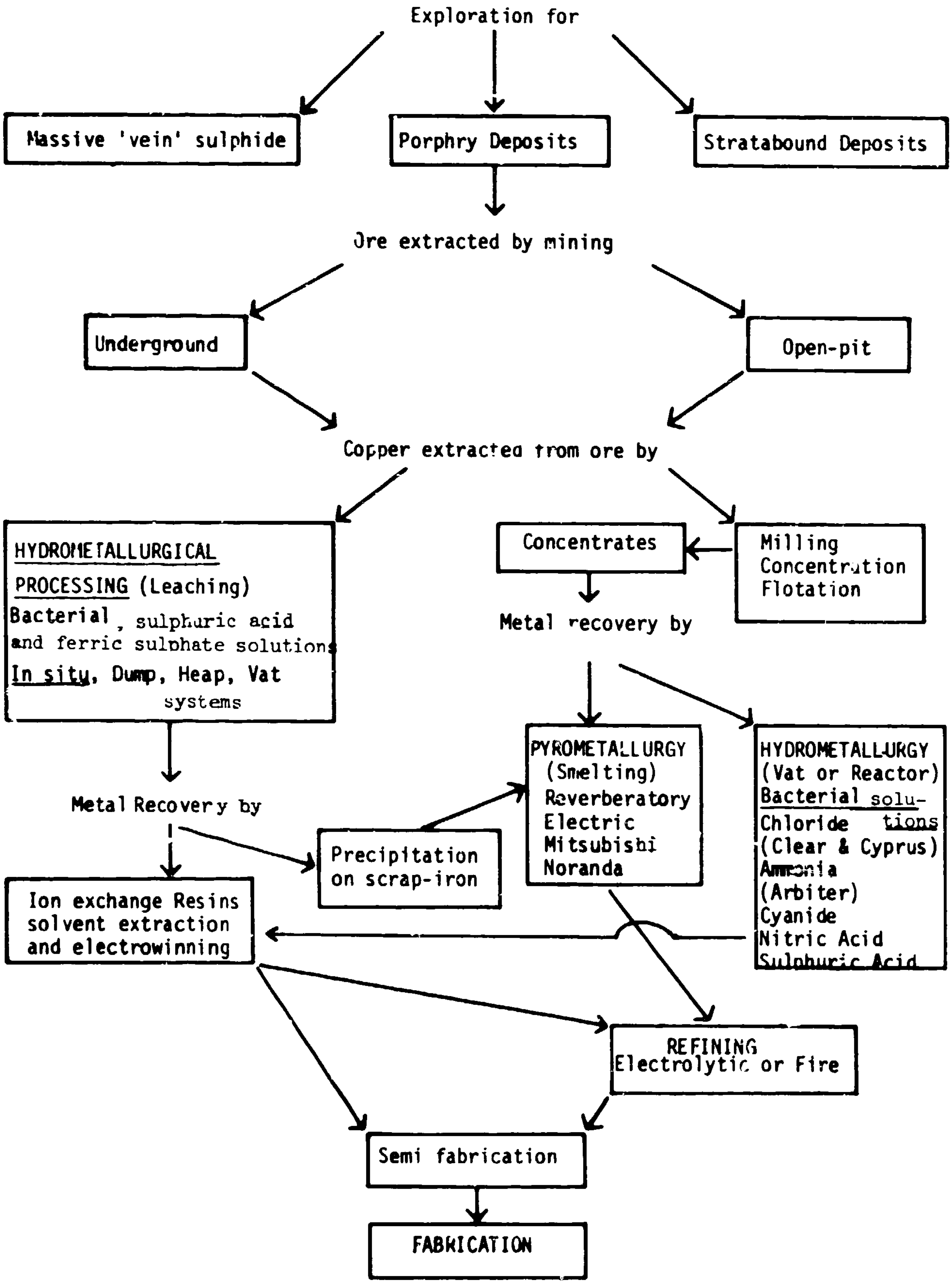
These deposits occur in veins, pods and lenses. Copper content varies from 1-5 per cent, and the volume of ore from several thousands to several million tons. The most important reserves are located in Australia, South Africa, Namibia, Cyprus, east Canada and, to a lesser extent, Latin America. Lead and zinc are the most commonly associated by-products. Since these deposits are of relatively high grade and, being more accessible, were some of the first types of deposits to be exploited, it is probable that there exist at these mine sites dumps of what was previously considered waste to which bacterial leaching might be effectively applied.

### 1.1.2 The copper production process

The main stages of the copper production process are illustrated in figure I and are briefly outlined below.

Figure I

BACTERIAL LEACHING AND THE COPPER PRODUCTION PROCESS




Source: A. Warhurst, "A Study of the Major Copper Producing Developing Countries in Relation to the World Copper Industry", mimeo (Brighton, Science Policy Research Unit, University of Sussex, 1980).

1.1.2.1 Mining

At present, 55 per cent of the world mine production of copper originates from open pit mines and 45 per cent from underground operations. Porphyry deposits, due to their widespread and disseminated mineralization characteristics, are suitable for relatively low-cost, open-pit bulk mining methods. The form and location of the mineral deposit determine the amount of overburden which has to be removed during the preproduction period in order to uncover the ore. In some large-scale open-pit mines, millions of tons of marginal ore and waste may be dumped requiring large areas of land, involving high costs of transportation and presenting pollution problems since natural leaching processes produce acidic effluents.

Natural leaching of marginal ore may be enhanced through optimizing related bacterial and chemical reactions either as an ongoing operation alongside conventional process routes, after the main ore body has been worked when ore grades have declined sufficiently to make the copper content worth recovering; or, when additional capacity is required at later processing stages. This indicates that generally it may be advisable to prepare relatively higher grade dumps for this eventuality.

The rock type and explosives methods will determine how the material shatters during mining and thus, for example, the extent of surface area exposed for leaching or the amount of preliminary crushing required at the next stage of the copper production process.

1.1.2.2 Metal recovery

Ore analysis is a prerequisite to metal recovery - primarily to determine a cut-off grade and consequently which material should be sent to the dump and which for processing; and secondly, to determine mineralogy and chemical composition and thus the optimum process route for metal recovery.

Sulphide ores are usually treated by pyrometallurgy (smelting), and oxides by hydrometallurgy (leaching).

1.1.2.2.1 Pyrometallurgy

Sulphide ores are first milled (crushed and ground), then mixed with reagents and concentrated by the process of flotation. The copper particles adhere to the bubbles and move to the surface while waste particles sink as tailings. The copper concentrate produced has a copper content of between 12-30 per cent.

The next stage is smelting which proceeds in three basic steps. Roasting reduces the sulphur content. Smelting then breaks down the crystalline structure of the minerals by an oxidation process. This produces a copper matte (containing up to 40 per cent copper) which, in its molten form, is converted and separated into blister copper (which is between 97-99 per cent pure) and an iron-silicate slag (which may be worth reprocessing).

Since blister copper is too impure for most industrial applications, refining is necessary. This is usually carried out by a fire process (using a reverberatory furnace) if the feed has a low by-product content, or by electrolysis. The resulting cathodes are sold directly to the semifabricators, or cast into shapes like the wire bar. At the semifabricating stage refined copper is worked into forms like sheets, strips, tubes and wire for subsequent manufacture into copper-bearing goods.

1.1.2.2.2 Hydrometallurgy and bacterial leaching

Copper ores containing oxide minerals are usually treated by leaching. The minerals, usually insoluble in water, are treated to form a solution containing the metals to be recovered. The ore is first crushed and then deposited in vats; acid, normally sulphuric, is percolated through the mixture. Then, depending on the recovery process route followed, cement copper can be produced by precipitating the copper from the leach solution onto scrap iron, or electrowon cathodes can be produced by electroplating copper cathodes directly from the leach solution. Smelting is usually necessary only in the production of cement copper. An alternative process route, using ion-exchange resins, permits the production of high quality cathodes pure enough for wire production without further refining.

Less commonly, at least at present, some sulphide minerals may be recovered by hydrometallurgical methods. Bacterial leaching is usually employed to extract copper from dumps, but has also been employed in heap and in situ systems (see 2 and 3 below). Bacterial, chloride, ammonia and cyanide solutions also have been tried in experimental confined systems in the United States and Canada. The four main methods of bacterial leaching are briefly outlined below in order to locate them in the copper production process. Details of the mechanism at work and of actual plant design are given in sections 1.3 and 1.4.

(1) Dump leaching

This is the most common type of leaching system. Dumps contain waste material considered at the time of mining uneconomic for metal recovery. Waste rock, the grade of which depends on the geology and age of the mine, is normally uncrushed and the dump bases unprepared for leaching.

With time rain water, or more commonly acified mine water, percolates through the dumps and, due to a combination of chemical and biological reactions, gradually leaches out the contained mineral content. Dissolved copper ions are thus suspended in a ferric sulphate and sulphuric acid effluent which emerges at the base. This is often allowed to enter drainage systems and since the pH is generally less than 2.5 it forms a dangerous pollutant. However, the copper ions can be recovered from the effluent enabling the recuperation of the metal and in the process returning the ferric ions back to their less pollutant ferrous state. The barren solution can then be recruited over the dumps.

It was probably at the Rio Tinto mines in Spain where copper was first commercially recovered on a large scale in this way. 2/ Concessions were granted for the recovery of copper from acid mine waters as early as 1670, and from leach liquors from 1752.

The role of microorganisms in the leaching process was not recognized until the main bacterium involved - T. ferrooxidans - was discovered and characterized in the late 1940s 3/ and the Kennecott Copper Corporation began researching the process in the 1960s.

Most modern dump leaching operations are on a very large scale containing many thousands of tons of rock. Some characteristics of the world's major commercial operations are presented in annex I.

(2) Heap leaching

Heaps can be distinguished from dumps because they are constructed intentionally for leaching. For example, they may be placed on impervious pads, or designed in a form to ensure maximum aeration. The ore may also be crushed to ensure efficient contact between the solution and sulphide particles. Heaps are usually composed of marginal ore containing a mineral content too low or too dirty to be smelted and too high to be discarded as waste. Defined in this way, the Cananea marginal ore finger heap system in northern Mexico is probably the only large-scale industrial operation of this type in the world. 4/

(3) In situ leaching

An *in situ* leaching system is an ore body leached in place, usually after preparation by blasting to shatter rock and make the mineral surfaces accessible. Leach solution is either percolated down from the surface or pumped under pressure into drill holes. "Pregnant" solution may be recovered from adjacent holes or from horizontal drives underlying the ore body. In some situations the natural leaching process may be so far advanced that copper ions are simply recovered directly from the emanating acified mine water. Examples of industrial operations of this type include Old Reliable in Arizona, United States, Cananea in Mexico, Kosaka Mine in Japan, Cerro de Pasco in Peru and El Teniente in Chile. (See also annex I.)

(4) Vat or confined system leaching

Bacterial leaching may also be carried out through the percolation or agitation of material, depending on whether the ore is ground or crushed, in vats or reactors. Higher grade ores and concentrates may be leached effectively in this way since conditions can be more readily controlled to optimize the process. Again the metal-laden solution can be recycled to allow the concentration to build up to a level suitable for solvent extraction. As yet this process has only reached the reactor and pilot plant stage and there is a danger that high concentrations of ions in a solution inhibit bacterial activity. However this process may become increasingly important in the future particularly if genetic engineering plays a larger role in bacterial leaching.

#### 1.1.2.2.3 Solvent extraction

Solvent extraction is an increasingly popular hydrometallurgical method for metal recovery, and also an alternative to scrap-iron precipitation. The dissolved copper in large volumes of pregnant acid solution (aqueous) is transferred to a small volume of organic (usually kerosene) solution to which reagent (e.g. LIX-64) has been added. The aqueous and organic phases are mixed and the dissolved copper values are transferred from the former to the latter. A settling action then separates the two phases. The aqueous is recycled back to the leach system, and the copper values are stripped from the organic to provide the feed for electrolytic refining. The solvent extraction process is both continuous and self-regulating.

A diagram of the solvent extraction flow-sheet is given in figure II.

### 1.1.3 Technical change and trends in the development of the copper production process

The potential of bacterial leaching is located in the context of four main sets of trends which characterize the development of the world's minerals industry.

These trends are of an economic and environmental nature. They are principally:

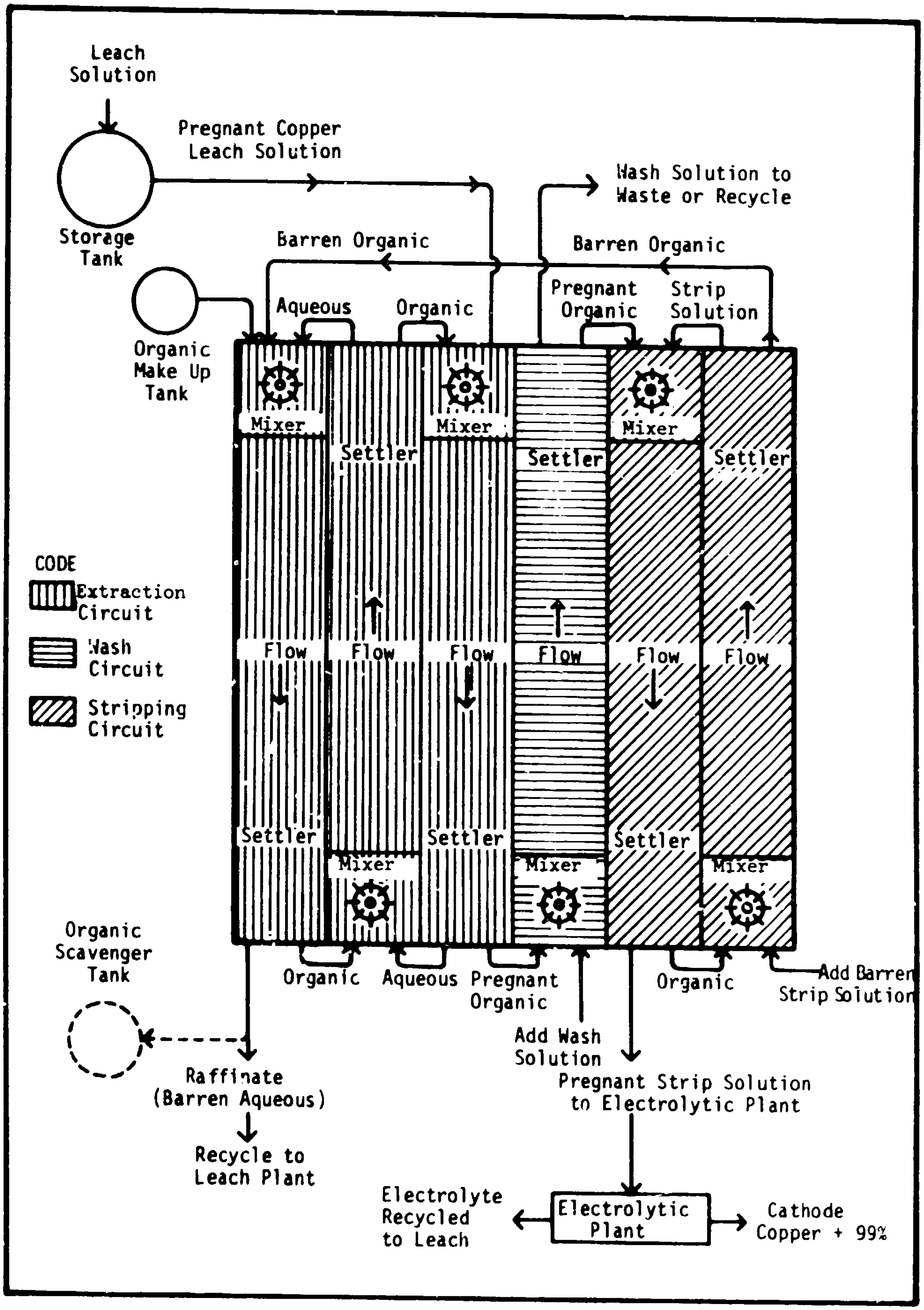
(1) The depletion of reserves and the decline in ore grade;

(2) Concern about environmental pollution and stricter government regulations;

Figure II

FLOWSHEET FOR THE SOLVENT EXTRACTION

OF COPPER LEACH SOLUTION




SOURCE: "Solvent Extraction, Flowsheet Study", Deco Trefoil, Nov.-Dec. 1965.

(3) Rising investment, energy and input costs;

(4) Low and unstable metal prices.

Until the beginning of the twentieth century, copper ore could only be mined and processed economically if it contained more than 10 per cent of the metal. Exploitation of deposits was therefore geographically restricted mainly to the locations of massive sulphide bodies. Thereafter increased industrial demand made it necessary to develop methods for extracting and recovering copper from the higher tonnage, through lower grade, porphyry deposits. In this context, mass open-pit mining methods developed in the United States were introduced and the flotation technique of enhanced mineral concentration was developed. Since then improvements such as larger-scale mining operations, polymetallurgical process routes, increased mechanization and advanced instrumentation and process control have combined to hold down the real cost of producing copper in the face of a declining grade of mined ore and a decline in the price of copper in real terms (see tables 1 and 2).

Table 1. The decline of average mineable grade of ore with time and corresponding changes in the cost of mining copper ore

| Date | Average mineable grade | Cost/lb copper (in 1970 dollars) |
|---|---|---|
| 1840 BC (est.) | 15 | 25 |
| 1540 AD (est.) | 8 | 10 |
| 1900 | 4 | 0.64 |
| 1910 | 1.9 | 0.44 |
| 1920 | 1.6 | 0.30 |
| 1930 | 1.4 | 0.33 |
| 1940 | 1.2 | 0.30 |
| 1950 | 0.89 | 0.30 |
| 1960 | 0.73 | 0.37 |
| 1970 | 0.60 | 0.58 |
| 1983 | 0.50 | |

Source: Table based on data from "Porphyry Copper Cast Study", Open University 533PC, 1976 and reprinted from documentation published in 1975 by the Committee on Mineral Resources and the Environment (COMRATE), National Academy of Sciences, United States.

Table 2. Average copper prices, 1950-1979

| Year | International Price Indices (1975=100) | Copper dollars per ton US market | |
|---|---|---|---|
| | | Nominal prices | Real prices |
| 1950 | 33 | 468 | 1 418 |
| 1951 | 40 | 534 | 1 335 |
| 1952 | 41 | 534 | 1 302 |
| 1953 | 39 | 635 | 1 628 |
| 1954 | 38 | 655 | 1 724 |
| 1955 | 38 | 827 | 2 176 |
| 1956 | 40 | 922 | 2 305 |
| 1957 | 41 | 652 | 1 590 |
| 1958 | 41 | 568 | 1 385 |
| 1959 | 42 | 687 | 1 636 |
| 1960 | 43 | 707 | 1 644 |
| 1961 | 43 | 660 | 1 535 |
| 1962 | 42 | 675 | 1 607 |
| 1963 | 43 | 675 | 1 570 |
| 1964 | 43 | 705 | 1 640 |
| 1965 | 44 | 772 | 1 755 |
| 1966 | 45 | 797 | 1 771 |
| 1967 | 45 | 843 | 1 873 |
| 1963 | 43 | 923 | 2 147 |
| 1969 | 43 | 1 048 | 2 437 |
| 1970 | 48 | 1 272 | 2 650 |
| 1971 | 52 | 1 134 | 2 181 |
| 1972 | 57 | 1 116 | 1 953 |
| 1973 | 69 | 1 298 | 1 881 |
| 1974 | 87 | 1 690 | 1 943 |
| 1975 | 100 | 1 401 | 1 401 |
| 1976 | 101 | 1 517 | 1 502 |
| 1977 | 111 | 1 451 | 1 307 |
| 1978 | 126 | 1 451 | 1 152 |
| 1979 | 143 | 2 033 | 1 422 |

Source: Precios de los Metales, a paper submitted to a seminar organized by the Economic Commission for Latin America (E/CEPAL/SEM.3/R.4.), June 1982.

By the early 1970s, it was possible to mine and process ore containing only 0.6 per cent copper. Current high prices for by-products like gold and silver mean that new mines are now being brought on stream containing polymineralic deposits with contained copper contents as low as 0.5 per cent. Bacterial leaching further allows the extraction of the metal from deposits containing as little as 0.3 per cent copper. This figure by itself however is slightly misleading; the feasibility of leaching such low grades may in part depend upon coexisting operations at the mine site involving the extraction and recovery of higher grade copper by conventional methods, that is, where bacterial leaching is employed as a relatively low-cost method of augmenting mine capacity.

The costs of operating and bringing a mine on stream have risen substantially over the last few decades. Figures presented by P.M.J. Gray clearly demonstrate this: a present-day copper mine producing a concentrate from 0.6 per cent copper sulphide ore at 90 per cent recovery using a total of 40kWh/tonne of ore in the mill and paying 5c/kWh for power, and US$ 2/tonne of ore for flotation reagents, would incur costs of US$ 740/tonne of copper in concentrate. However, 30-40 years ago a producer might have been treating a 2.0 per cent copper ore at 90 per cent recovery using 20 kWh/tonne of ore for reagents (in 1980 US$), which is equivalent to about US$ 16/tonne of copper in concentrate. 5/ These rocketing investment and operating costs are forcing mining management to consider new, innovative methods as well as re-examining existing techniques to maintain the economic viability of current operations.

Technical developments over the last decade in response to these trends mean that there now exist a number of technically viable options to be considered during process route selection. These can be grouped into pyrometallurgical and hydrometallurgical alternatives. (A detailed survey of all the current process routes available is presented in annex II.)

1.1.3.1 Pyrometallurgical alternatives

Recent innovations in pyrometallurgy include matte-making processes such as flash furnaces, oxygen sprinkling and electric furnace smelters, and continous matte-making and converting techniques.

Reverberatory smelting, widely accepted until recently as the best process for treating sulphide concentrates, is now virtually obsolete because of its associated environmental problems and its high energy requirements. Other matte-making processes, notably flash furnaces, oxygen sprinkling smelting and electric furnace smelting, have been developed and have received widespread and successful commercial application. They enable the containment and recovery of pollutant sulphurous gases from which a marketable sulphuric acid easily can be made. Electric furnace smelting may be very economical where a relatively low-cost electric power source is available.

Continuous processes, combining matte smelting and converting in one vessel or a series of linked vessels, have been developed recently in order to reduce both energy requirements and pollution. The Noranda and Mitsubishi processes are now at the industrial plant stage and exhibit excellent potential for confining and concentrating off-gas streams. 6/

1.1.3.2 Hydrometallurgical alternatives

In response to the same set of trends listed in section 1.1.3, a series of hydrometallurgical techniques are either available or being developed.

As higher grade deposits are depleted, an increasing number of new mine sites are low-grade (0.5-1 per cent copper content) porphyries of a complex (i.e. multimineral assemblages) and dirty nature. This presents a need to stretch further the mine capacity and to compensate for declining ore grades by recuperating resources not previously exploited like dumps and marginal overburden.

Similarly, it is becoming necessary to recover associated by-products and to take out pollutant elements like arsenic and bismuth.

Conventional practice in metal extraction involves producing a concentrate of the valuable mineral, as outlined in section 1.1.2.2 above. However, impure and multimineral feeds are much more expensive to smelt, since they require the addition of expensive chemicals and the "grafting on" of energy-intensive process routes to extract associated by-products and pollutant off-gases. In contrast, with leaching there is no need to remove inert gangue.

Thus it may be feasible in some instances to eliminate physical milling and concentration methods from base metal extraction for low grade sulphide minerals - which is one of the most energy-intensive stages of the copper production process. 7/

Of great significance to the present discussion is the fact that a number of investigations into the bacterial leaching of sulphide concentrates in reactors indicate that in certain cases leaching in this way may provide an alternative to smelting (see figure III). R.O. McElroy and A. Bruynesteyn have devised a method for the continuous leaching of chalcopyrite, bornite and chalcocite concentrates. They showed that electrowinning grade leach solutions could be obtained with the former (the most refractory) in 50 hours, that gold and silver values could be recovered, and that the process was suitable for small-scale operations at the mine site. Using 1973 energy prices, they present data which indicates that the process was marginally competitive with conventional smelting. Negligible atmospheric emissions, and facilitated recovery of dilute sulphuric acid suitable for leaching oxide ore, mill tailings and certain waste dumps, imply that confined bacterial leaching may form part of an economically efficient primary processing route for copper concentrates in the near future. 8/

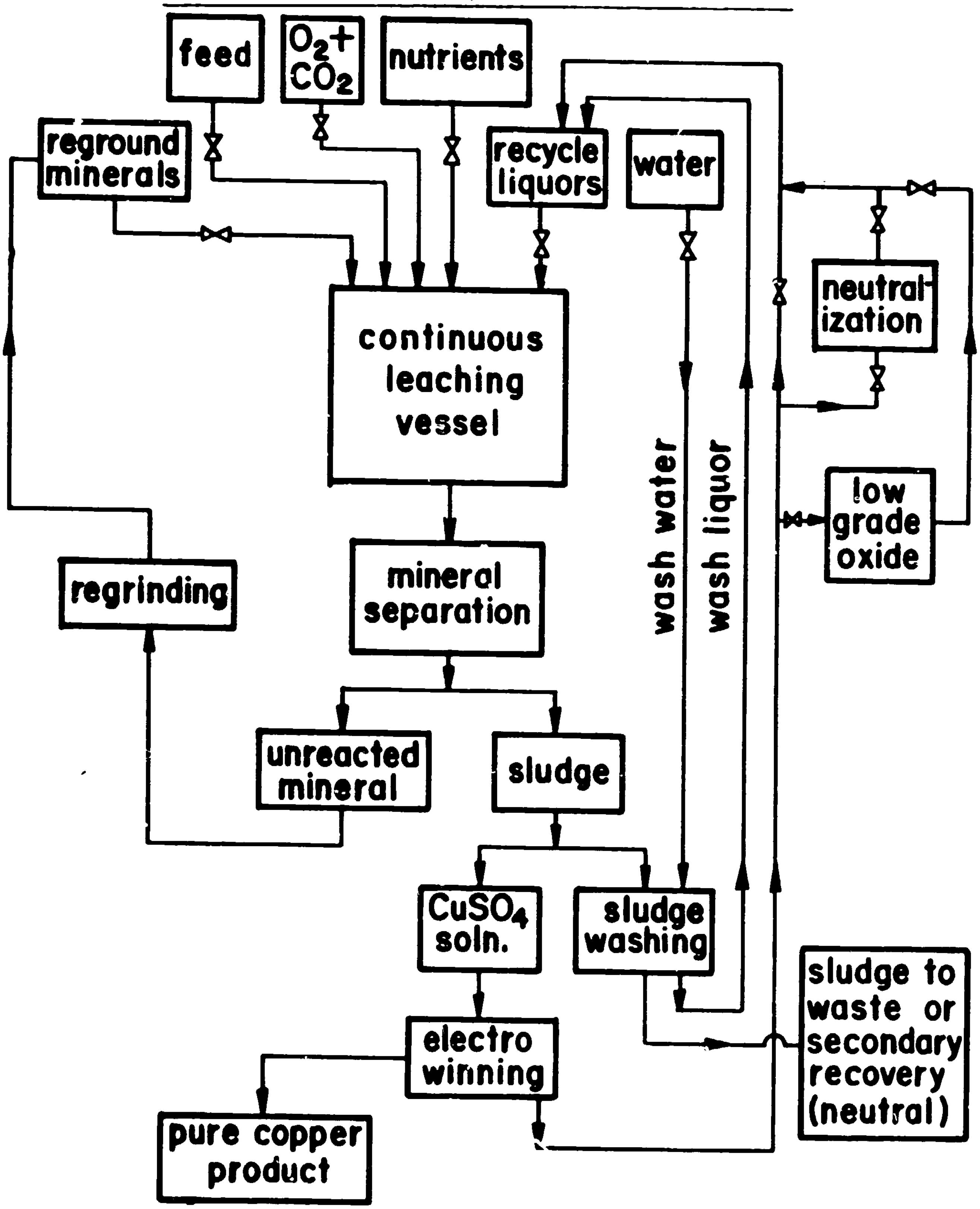
Furthermore, in the area of hyrometallurgy, processes for leaching sulphide minerals and mixed ores using chloride, cyanide and ammoniacal solutions have been developed.

Sheritt Gordan Mines, Canada, has developed a pressure leaching technique. It is used to treat finely ground copper sulphides in aqueous sulphuric acid with oxygen or air at high pressures. Copper recovery is slightly lower than by established pyrometallurgical processes, precious metals remain in the residue, and the overall economics apparently are high; however, the process does provide a high yield of elemental sulphur, thus preventing sulphurous pollution.

The Duval Corporation, United States, and Cyprus Mines have produced chloride leaching systems, the CLEAR and Cymet processes respectively. Although present operating costs are apparently high, and a satisfactory metal recovery process (perhaps using solvent extraction technology) has to be found, the advantage of these chloride processes is that they are small scale, require less energy than their pyrometallurgical equivalents, and allow the recovery of sulphuric acid and precious by-products. However it remains to be investigated whether pollution from sulphurous gas may only be reduced at the cost of pollution from chemically toxic effluents as a means to evade regulations. 9/

FIGURE III

FLOW-SHEET OF COPPER SULPHIDE CONCENTRATE LEACHING PROCESS




SOURCE: A. Bruynesteyn and D. W. Duncan, "Biological leaching of sulphide ores", a paper presented at a Conference on Means of Exploiting Low Grade Ores, held at the United Nations, New York, in 1972.

Sheritt Gordan and Anaconda have both developed ammoniacal leaching systems for complex copper-containing sulphides. Ammonium sulphate may be recovered for sale, eliminating effluent pollution problems. However, these processes are still at the development stage.

It is not realistic to conclude that one type of process - either pyrometallurgy or hydrometallurgy - will dominate because it is found to be the minimum cost process. The geological peculiarities and geographical location of each mine site mean that each is a special case which requires a process route to be tailored to it rather than one which simply meets more general requirements.

Although each mine will have its own set of production costs, and no attempt is made here to carry out an economic analysis, the differences in investment costs between these processes is apparently large. Recently it was reported that the investment required for a concentration smelter and refinery is usually between US$ 300-800 million while the investment for a dump operation is generally in the range of US$ 5-20 million. For a solvent extraction plant an investment of between US$ 10 and 20 million is required. 10/

It is generally acknowledged that the operating costs of bacterial leaching are relatively low, little energy is required for pumping and if the process is working efficiently the acidity is self-regulating and requires no additions. However, solvent extraction is more energy-intensive than smelting and, although a purer grade of copper results, in every case a trade-off decision must be taken.

Some recent economic statistics on the investment costs and production of copper for some large-scale bacterial leaching operations are presented in table 3 for reference. In addition, in table 4, an economic comparison is made of pyrometallurgical and hydrometallurgical alternatives for a plant which will be located near Santiago in Chile. However, this data is not completely reliable since neither ore grades nor volumes are mentioned.

Table 3. Capital investment for some commercial bacterial leaching operations in the United States

| | | | |
|---|---|---|---|
| 1. | Miami Copper, Arizona: | Sulphides<br>Leaching in situ, SX[a] EW[b]<br>US$ 6 million (1976) | - 20,000 lbs/day<br>- 3,000 GPM[c] |
| 2. | Pinto Valley, Arizona: | Sulphides<br>Dump leaching, SX EW<br>US$ 26 million (1981)<br>US$ 12 million of which for SX | - 21,500 lbs/day<br>- 6,000 GPM |
| 3. | Baghdad, Arizona: | Sulphides<br>Dump leaching, SX EW<br>US$ 5 million (1969) | - 40,000 lbs/day |
| 4. | Pudahuel, New Mexico: | Oxides and sulphides<br>Thin layer leaching, SX EW<br>US$ 70 million (1980) | -100,000 lbs/day |
| 5. | Bluebird, Arizona: | Oxides<br>Heap leaching SX EW<br>US$ 2.5 million (1968) | - 40,000 lbs/day |

Source: E. Oak, Lixiviación bacterial de minerales en pila/botadero, a paper presented at the International Symposium on the Current Technology of Copper, held at Bucaramanga, Colombia, in December 1982.

a/ SX - solvent extraction; b/ EW - electrowinning; c/ GPM - gallons per minute.

Table 4. Economic comparison of proposed alternative process routes for a mine near Santiago, Chile

| | Flotation, smelting and refining | Bacterial leaching, solvent extraction and electrowinning |
|---|---|---|
| Annual production of copper (in tons) | 36 800 | 30 000 |
| Cost of installed plant (US$ million) | 370 | 100 |
| Infrastructure (US$ million) | 20 | 16 |
| Capital investment (US$ million) | 390 | 116 |
| Production costs (cents/lb) | 75 | 31 |
| Rate of return, (%) | 15 | 45 |

Source: E. Oak, ibid.

It cannot be overemphasized that the cost structure of installing and of optimizing a bacterial leaching project is highly dependent upon the natural characteristics of the mine and its location. Local knowledge of these factors and their implications for technology development is thus essential. For example, the rock type will determine the necessity for preliminary crushing after dynamiting, the addition of extra acid or the special design of finger dumps; the hydrogeology and soil types of the location of the leaching operation will determine the need for prior ground surface preparation; and the availability and characteristics of local mine water and vibrant bacteria will ultimately determine the efficiency of bacterial leaching for a given mine.

Finally a discussion of technical change in the minerals industry would not be complete without outlining further applications of bacterial leaching technology in mining and minerals processing.

### 1.1.3.3 Further examples of actual and potential biotechnology applications in the mining and minerals processing industry

#### 1.1.3.3.1 Uranium leaching

Although uranium leaching is not carried out on any great commercial scale, it is becoming increasingly important. The bacterial leaching of uranium is exclusively an indirect process, since no known organisms are able to derive energy from the oxidation of uranium oxide. *T. ferrooxidans* oxidize ferrous iron and pyrite (according to reactions [4] and [19], section 1.3.2.1) to produce the oxidant ferric ions, which react with reduced uranium:

$$UO_2 + Fe_2(SO_4)_3 \rightarrow UO_2SO_4 + 2FeSO_4 \qquad [1]$$

Ferric iron ore is regenerated by the bacteria, and sulphuric acid - necessary to maintain the oxidized uranium in solution - is added and/or generated by the bacterial oxidation of pyrite.

Uranium is mainly recovered by bacterial leaching using in situ methods, particularly in abandoned mines. 11/ Underground workings are sprayed with water to encourage microbial action, and the metal is solubilized from the rock walls of the mine. The lixiviant collects at the lowest point in the mine, from where it can be pumped to the surface and the uranium recovered. Examples of such applications can be found in the Elliot Lake region in north Ontario in Canada. Prospects for further applications of uranium leaching include deep solution mining. This involves fracturing the ore body with explosives and circulating lixiviant generated in vats of fermenters on the surface. A.W. Fletcher describes a joint project undertaken by the Kennecott Copper Corporation and the United States Atomic Energy Commission. The intention was to fracture a deep low grade copper ore body by a contained underground nuclear explosion prior to in situ leaching. 12/

The advantages of uranium leaching usually quoted include: no rock is brought to the surface, thereby eliminating risks to miners' lives and saving on labour costs; no solid waste is created and liquid wastes can be minimized by recycling the leaching solutions; and the process is ideal for applications involving low-grade and finely disseminated ores which cannot be economically treated by conventional techniques.

There are, however, substantial disadvantages and dangers associated with using this method, which must be considered in any related investment decision.

One disadvantage is that rates of extraction and recovery are difficult to predict and therefore investment decisions are very risky. 13/

Secondly, in situ leaching of uranium has resulted also in considerable microbial fouling. 14/ Macroscopic growths of microorganisms have been observed to cause plugging and the generation of gases which could produce airlocks in the leach system. The injection of chlorine gas, to enhance solution flow and remedy the problem, is expensive. Thirdly and most dangerous, however, is the environmental pollution that can be generated by the seepage of acid solution containing highly toxic dissolved uranium ions. It is very difficult to predict solution flow patterns underground, and contamination of ground-water zones could easily result. Deep solution mining and ore shattering are especially precarious; and a detailed knowledge of the structure of the metal-bearing rock and of the surrounding geological formations is a prerequisite to the undertaking of such a project. Such a knowledge is often lacking in developing countries where geological surveys have not been carried out to the same extent and in such detail as in the developed countries. So, while conventional uranium mining is the most hazardous type of mining in the world, the reduction of such activity should not be at the cost of pollution of local crop and water supplies.

1.1.3.3.2 Zinc and lead sulphide leaching

Zinc and lead sulphides often occur together in a finely disseminated form. Flotation methods are not able to separate the metals, and the amount of lead occurring in the flotation concentrate is usually too high for the material to be fed to zinc smelting operations. Bacterial leaching of the concentrate, however, could result in the separation of the metals by the formation of a soluble zinc sulphate and insoluble lead sulphate. Zinc could then be removed from the solution by electrowinning, while the insoluble residue would eventually become enriched to the extent that economic recovery was possible. 15/

1.1.3.3.3 Nickel and cobalt sulphide leaching

Bacterial leaching processes have also been observed in nickel and cobalt sulphide deposits. C.L. Brierley recently noted that over seven billion tons of low grade nickel, with a content of 0.290 per cent, was not mined due to the inefficiencies of current extractive technologies and detrimental environmental effects. However, bacterial leaching could recover this material which, at current prices, is worth US$ 60 billion, as well as some 400 lbs of associated cobalt worth US$ 10 billion. 16/

1.1.3.3.4 Arsenopyrite leaching

Although very little research has been carried out in this area, it has been observed that arsenic is not toxic to leaching bacteria. Therefore, it is possible that arsenopyrite may be extracted bacterially from smelter feeds thus enabling a significant reduction of arsenic pollution from associated off-gases. This is particularly relevant to the Andean countries since arsenopyrite is found in association with copper in porphyry sulphide zones.

1.1.3 3.5 Bacterially-assisted gold recovery

Gold is often found disseminated within the crystal lattice of pyrite. The bacterial dissolution of pyrite (equation [13], section 1.3.2.1) frees the gold, enabling it to be recovered by cyanidization. This process is being applied in the United States and Canada; in Ghana, investigations into the possible application of this technique to the recovery of gold from local deposits are currently being carried out and there is apparently much potential for its application in the Nazca region of Peru and in Bolivia, Colombia and Ecuador.

1.1.3.3.6 Metal recovery using bacteria

Certain microorganisms are able to remove useful or harmful metals from solutions; although there are no existing examples of the industrial application of these natural processes. Trace elements can be accumulated by bacteria from solutions that contain more of the metals than is normally encountered in the environment. Under these conditions, significant quantities of toxic metals like silver, cadmium, lead and thallium may be accumulated also. This accumulation of metals apparently may be achieved by introcellular uptake and binding to organism surfaces. 17/

1.1.3.3.7 Bacterial leaching of oil shale

T. ferrooxidans and Desulfovibrio also can be used to leach oil shale in order to effect matrix dissolution. Elemental sulphur is used as an energy source. However, it would probably be impractical to use such a system commercially unless sulphur could be generated by Desulfovibrio using some inexpensive and readily available substrate. 18/

1.1.3.3.8 Bacterial leaching of pyrite from high sulphur coal

Apparently mixed cultures containing mainly T. ferrooxidans and T. thiooxidans were effective in removing pyritic sulphur from 20 per cent slurries of a commercial grade of pulverized coal. 19/ The beneficiation obtained ranged from an average of 4.6 per cent total sulphur to about 1.5 per cent total sulphur. Current research also suggests the possibility of microbial removal of the organic sulphur fraction of coal. P.R. Dugan and W.A. Apel claim they have demonstrated the potential for commercial-scale desulphurization of coal operations; however, only technical data is presented. Since a high sulphur content is a significant constraint in coal development, if this process could be developed on a commercial scale the implications for coal-producing developing countries would be enormous.

## 1.2 The implications of technical change in the minerals industry for developing countries and the potential of bacterial leaching

The trends affecting the minerals industry and the related technical changes discussed above have important implications for developing countries. This is because the majority of both developed and unexploited porphyry deposits are located within their boundaries.

### 1.2.1 Mineral reserves and planned mining projects

According to the results of three separate surveys, world copper reserves are estimated to be between 450 m-500 m tons of contained copper. Of these, the developing countries possess nearly 60 per cent, which is one and a half times their share of world production. Chile possesses nearly 20 per cent of world reserves, Zambia 7.3 per cent, Peru 6.5 per cent, Zaire 5 per cent, Philippines 3.7 per cent and Papua New Guinea 2.8 per cent. [20]

At least 75 per cent of the reserves of Chile, Zaire and Zambia are in mines already in operation, which suggests that as the copper deposits are depleted, these mines have the best potential for expanding output at less marginal cost to the operating enterprise and to the government for infrastructure.

This figure for world reserves, however, only accounts for a small percentage of world copper resources. Resources are much more difficult to estimate. Recent estimates of copper resources have set a cut-off grade at around 0.1 per cent copper. (The cut-off grade for reserves is around 0.4 per cent copper while ordinary rock contains on average 0.005 per cent copper content.) On this basis, world resources have been estimated to be between

11 and 14 b tons of contained copper - the wide range obviously indicating the speculative nature of such estimates. Of these, 20 per cent are supposedly located in the United States, 15 per cent in the socialist countries and "significant proportions" are in Chile, Iran, Peru and the Philippines. 21/ However, these figures contain a bias towards the developed countries due to the disproportionate geological exploration that has taken place there. For example, only 5 per cent of the mineralized zone of Mexico and 10 per cent of that of Bolivia has been explored. 22/ (See also the geological map, figure IV below.)

Furthermore, recent advances in geological theory, concerning plate tectonics and the controlling mechanisms of copper porphyry formation indicate that predictions of old plate boundaries may lead to the discovery of new deposits in the near future. 23/

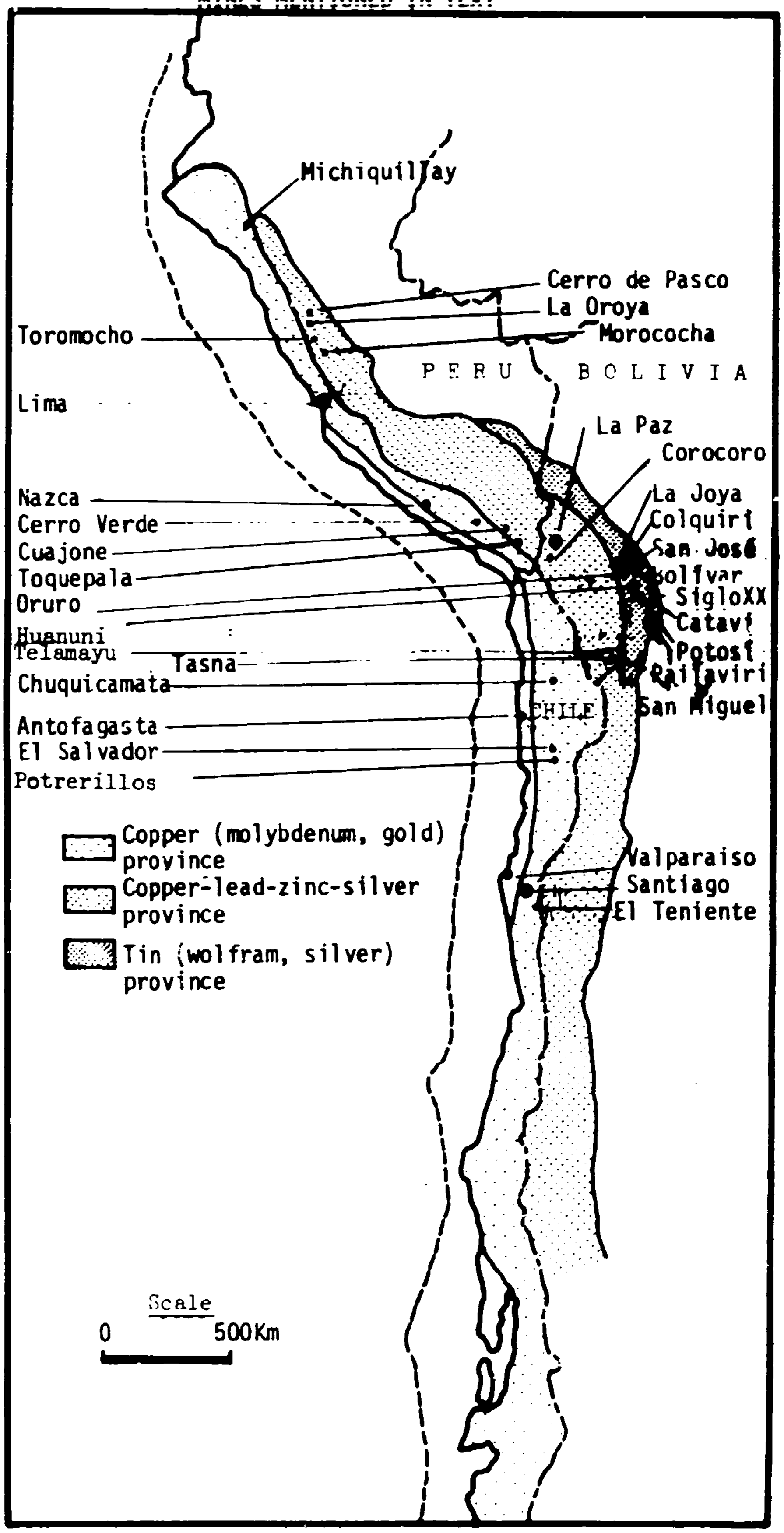
Obviously knowledge of resources in developing countries is essential since it will indicate the appropriate direction and methodology of exploration and technical change. These figures for resources also take on further significance when it is remembered that bacterial leaching at present can be applied to deposits of as low a grade as 0.1 per cent copper.

Assuming the continuance of the presently rising global demand for copper, it is evident that the majority of new copper projects are going to be based in the developing countries. This trend can be identified clearly in the recently published figures listing new projects for which definite plans have been announced and which are expected to be commissioned over the next five to six years. 24/ Developing countries with new copper mining or processing projects (the majority of which are sulphide prophyries) included in this list are: Algeria, Argentina, Brazil, Burma, Burundi, Chile, Colombia, Ecuador, India, Indonesia, Malaysia, Mauritania, Mexico, Namibia, Oman, Pakistan, Panama, Papua New Guinea, Peru, Philippines, Sudan, Venezuela, Zambia and Zimbabwe.

This implies that several countries are now selecting process routes for new mineral projects in the context of the economic and environmental trends noted above (section 1.1.2).

Figure IV.

SKETCH MAP TO SHOW METAL PROVINCES OF ANDEAN REGION AND LOCATION OF MINES MENTIONED IN TEXT




Source: Adapted from Richard H. Sillitoe, "Tectonic segmentation of the Andes: implications for magmatism and metallogeny", Nature, London, vol. 250 (1974), pp. 542-545.

### 1.2.2 The potential of bacterial leaching for developing countries

Given the present international climate, planners of new minerals' projects will have to consider a wide range of processes, which may even include unconventional alternatives, so that the treatment exhibiting the best overall economies can be found.

Within this context it can be argued that bacterial leaching may contribute to broaden the range of possible process routes available in three main ways.

First, the leaching of sulphide values from waste dumps of previous mining operations which worked with a higher cut-off grade, or the "flushing out" of old mines using in situ leaching techiques. These techniques recuperate "extra" mineral content and, in so doing, prevent natural pollution by uncontrolled acidic effluents.

Secondly, the leaching of overburden from newly-developed mineral deposits, and of marginal ore during ongoing operations, in heaps specifically designed to optimize the leaching process for short-term economic gain.

Thirdly, the more novel possibility of leaching sulphide concentrates in confined systems under carefully controlled conditions.

#### 1.2.2.1 The potential of dump leaching

Economic constraints such as high input (e.g. energy and materials) costs and low copper prices promise to lead to the adoption of new strategies by companies with older operations. As a mine approaches the end of its life, these companies may turn to extracting the last remaining copper values from dumps of previously uneconomic ore and from the mine itself using in situ leaching techniques. Such expansion would be at little marginal cost to the operating enterprise as a whole. The chemical and biological reactions are self-sufficient and only a modest amount of purchased energy would be required for pumping and solids handling. The copper concentrates thus recovered could be sent as feed to the smelter which, at this stage in the mine's life, would probably be running at under capacity anyway.

Most of the developing-country copper producers have long mining histories. In mines where cut-off grades have lowered over time, or where other minerals like silver or bismuth only were mined, there probably will exist dumps of currently economically viable copper ore. Older dumps, because of the unrefined ore selection techniques of the time, may contain more than 1 per cent copper.

In many developing countries transnational companies have been operating in unstable conditions with constant threats of nationalization and of policy changes regarding exports and profits. The tendency thus was to exploit the deposits in the most rapid and immediately cost-effective way. This meant treating only the high grade ore and dumping the marginal material. For example Anaconda and Kennecott, two companies which had operations in Peru and Chile, employed higher cut-off grades in their Latin American operations than in their United States ones. Furthermore, they engaged in long-term planning at their United States mines - which are roughly of the same sulphide porphyry type as their Latin American ones - and invested in bacterial leaching projects for the dumps there at Butte and Bingham. Although it would be difficult to evaluate this empirically it is another indication that dumps in developing countries may now contain economically viable unexploited mineral wealth.

Related to this, the organization of labour in the mines when there are short-term economic pressures may also affect the copper content of dumps. Mining activities are generally subdivided into morning, afternoon and evening shifts. Where the milling superintendent is under great economic pressure, and when management is not overseeing operations (as is usually the case in the latter two shifts), there is a tendency to adopt a temporarily and artificially high cut-off grade for crushing and concentrating. This means that the feed for smelting is of a purer and higher standard, which implies that the milling superintendent's job has been well done. As a consequence, however, waste may contain ore of a higher grade than is "officially" recognized (given that estimates of dump reserves are usually based on previous cut-off grades rather than geological evaluation).

The quality of dump ore may also depend on the nature of the rock type. If the ore naturally shatters into large particles and boulders, then waste material may contain concentrations of copper which weathering has broken up over time to expose leachable mineral-rich surfaces.

1.?.2.2 The potential of heap leaching

The financial requirements for mineral project investments are increasing and, despite nationalization of the industry in several copper-producing developing countries, there has inevitably developed an increased reliance on foreign investment. This has been in the form of either joint ventures or direct investment by wholly owned subsidiaries. An interesting recent phenomenon has been the move by the oil transnationals, which hold large financial surpluses, to invest in copper exploration, evaluation and production. This includes Standard Oil in Zaire, Amoco in Papua New Guinea, Shell in Peru, and Exxon in Chile. 25/ If this trend persists, any measure of control that was achieved by the developing countries through state-ownership of their copper industries may be in danger of being reduced. Loans for exploration and mine development are often conditional upon the participation of a specific foreign mining company (perhaps even a subsidiary of the firm that provided the finance or undertook the exploration) in the mineral project.

It is possible, however, that a bacterial leaching project may alleviate to a certain extent the resulting dependence. For example the majority of new mineral deposits are porphyries. These usually require open pit mining and thus the removal of large tonnages of overburden. This overburden, which often contains economic quantities of copper sulphides due to the disseminated nature of the ore deposits and its gradual boundaries, could be separated into waste proper and leachable ore. At relatively little additional cost to the mining operation as a whole - say less than US$ 50 m in relation to a mining project's investment costs of upwards of $1 billion - heaps could be constructed according to the optimal conditions for the leaching of that ore. The remuneration subsequently obtained (after a leach cycle of two to three years) could be used to offset the costs of developing the mine proper. In the same way revenue from dump leaching a previous mine's waste may contribute towards the cost of a new mine.

1.2.2.3 The potential of concentrate leaching

In view of the current problems facing pyrometallurgy and the growth of hydrometallurgy, it is expected that confined bacterial leaching systems will be considered an economic alternative to smelting in the future. Breakthroughs during the last six months at British Colombia Research Council, indicate that in the light of current energy costs, leaching of copper concentrates may be successfully carried out on a commercial scale at 60-70 per cent of the cost of a similar smelting operation. 26/ And this of course does not take account of the benefits associated with bacterial leaching arising from its negligible pollutant effect in contrast to other hydrometallurgical and pyrometallurgical methods. Although a weak sulphuric acid is produced (see section 1.3.2.1, reaction [8]), this can be recovered and marketed (for example, for use in the chemical leaching of oxides). Seepage of effluent into ground water is prevented because the system is closed. Obviously, in confined leaching systems far more human control can be exerted over the parameters affecting the leach process, so the potential for improving the process is enormous.

The majority of new projects and unexplored mineralized zones are in the developing countries and exploration endeavours and project development take decades. Therefore the possibility is very high that concentrate bacteria may form a primary process route alternative in these new projects; especially given the advances in biotechnology and the improvements being made to complementary solvent extraction recovery processes. However this requires a certain degree of independence and flexibility on the part of decision makers during the technical choice process when considering what was previously considered an "unconventional" alternative.

1.2.2.4 Overview

In spite of these arguments, there are only three industrial applications of bacterial leaching in developing countries. The oldest is at the state-owned mine of Cananea in northern Mexico, and the more recent is CENTROMIN's *in situ* and dump operation at Cerro de Pasco in Peru. Another dump leaching operation is run at the Bougainville mine in Papua New Guinea.

However, field-work during 1982 revealed that several developing countries are considering bacterial leaching during process route selection for new mineral projects.

In Chile bacterial leaching technology development is supposedly one of CODELCO's most important planned investments for next year. Impressive projects are in progress at Chuquicamata, El Teniente and Salvador. Disputada is also planning a huge heap leaching project for the marginal overburden to be removed during the development of its large porphyry deposit at Los Bronces. In Peru, bacterial leaching is planned to play an important economic role at Toromocho (CENTROMIN), Cerro Verde (MINERO-PERU), and Pativilca (Hochschild). Similar projects are being considered by Rio Tinto Zinc at Cerro Colorado in Panama, by COMIBOL at Tasna in Bolivia and by Colombia at their copper deposits at Mocoa, and by Argentina, Ecuador and India.

Indeed, the application of bacterial leaching may have significant implications for countries like India, which have large reserves of very low-grade copper yet not enough tonnage to make conventional processing alone economic. Biologically-produced cement copper could be recovered to supplement smelter feed, and thus make the overall operation economic. Most of India's reserves of 366 m tons contain only 1 per cent or less of copper. The National Chemistry Laboratory at Poona recently embarked upon a bacterial leaching project, with the aim of supplementing the indigenous production of 61,000 tons per annum. However, no mention has been made of commercial application and it appears that the project is still in its infancy. 27/

It is very difficult to analyse exactly why bacterial leaching technology development has not received the attention by developing-country mineral producers that the above arguments suggest it deserves. Various explanations may be given. These include: problems of fund allocation within companies; traditional conservatism of mine management regarding trying unconventional alternatives; established trading patterns with developed-country plant and equipment suppliers for conventional techniques and, perhaps, aggressive marketing behaviour by the latter in the light of the technical change trends observed above; and finally the fact that virtually all the examples of the commercial applications of bacterial leaching technology are to dumps of what was previously considered waste or marginal ore. That is, dumps which are mainly located in the industrialized countries (e.g. Canada, the Soviet Union and south-west United States), which were constructed before it was realized that parameters could be developed to optimize the microbial processes. So although these bacterial leaching operations account for more than 10 per cent of the production of United States copper, they generally have recuperation rates no higher than 40 per cent of the contained metal in a period of about five years. This may account for the widespread belief predominant in the mining industry that bacterial leaching is a low-cost operation with low and slow returns. The present paper argues against this traditional view.

In optimal conditions T. ferrooxidans and other bacteria can accelerate the oxidation and dissolution of sulphide minerals (and thus the creation of a highly acidic medium), as well as acting on them directly, by up to $10^6$ times the rate that occurs in the presence of air alone. Thus, according to laboratory and pilot plant research and depending on rock type and mine characteristics, if optimal conditions for bacterial growth are provided, recuperation rates of up to 90 per cent can be obtained for industrial heaps in time periods of less than two years. Recovery rates of 88 per cent were obtained by CENTROMIN, Peru, during the Andean Pact Copper Project, at its semi-industrial-scale heap leaching system at Toromocho.

The principal implication of all this is that there exists no precedent in the industrialized countries of optimized bacterial leaching operations on an industrial scale. There are no general models upon which the developing countries can design their leaching projects and, as a source of technology transfer, the potential of the industrialized countries is limited. Although, it should be added that throughout 1982 there was an increasingly large investment in applied R and D in the area of optimizing bacterial leaching of the main sulphide minerals in the developed countries by firms, institutes, universities and international technical and financial assistance organizations.

Thus, it is in this context that the next two sections explore the mechanisms of bacterial leaching in more detail; particularly the conditions controlling it and the related methods for the optimization of the process.

## 1.3 The mechanism of bacterial leaching

Bacterial leaching is fundamentally a natural process. The process has occurred since sulphide-bearing rocks were first formed thousands of millions of years ago; although it has been accelerated during more recent centuries through the exposure of mineral-rich material due to the mining of copper, iron, lead, zinc, silver, gold and coal.

One of the most important natural cycles is the sulphur cycle (figure V). Within this there exists a secondary process in which the element is cycled solely by the action of microorganisms; it is here that the bacterially-assisted oxidation of sulphur and sulphide minerals takes place. 28/ A wide range of metals can be dissolved from their sulphide form during these biological reactions which may be optimized to enable economic metal recovery.

The first step towards improving the efficiency of a natural process for economic gain is understanding the mechanisms at work. Taking this as a starting point, this section will discuss in turn the microorganisms, the associated reactions, and the factors controlling bacterial leaching.

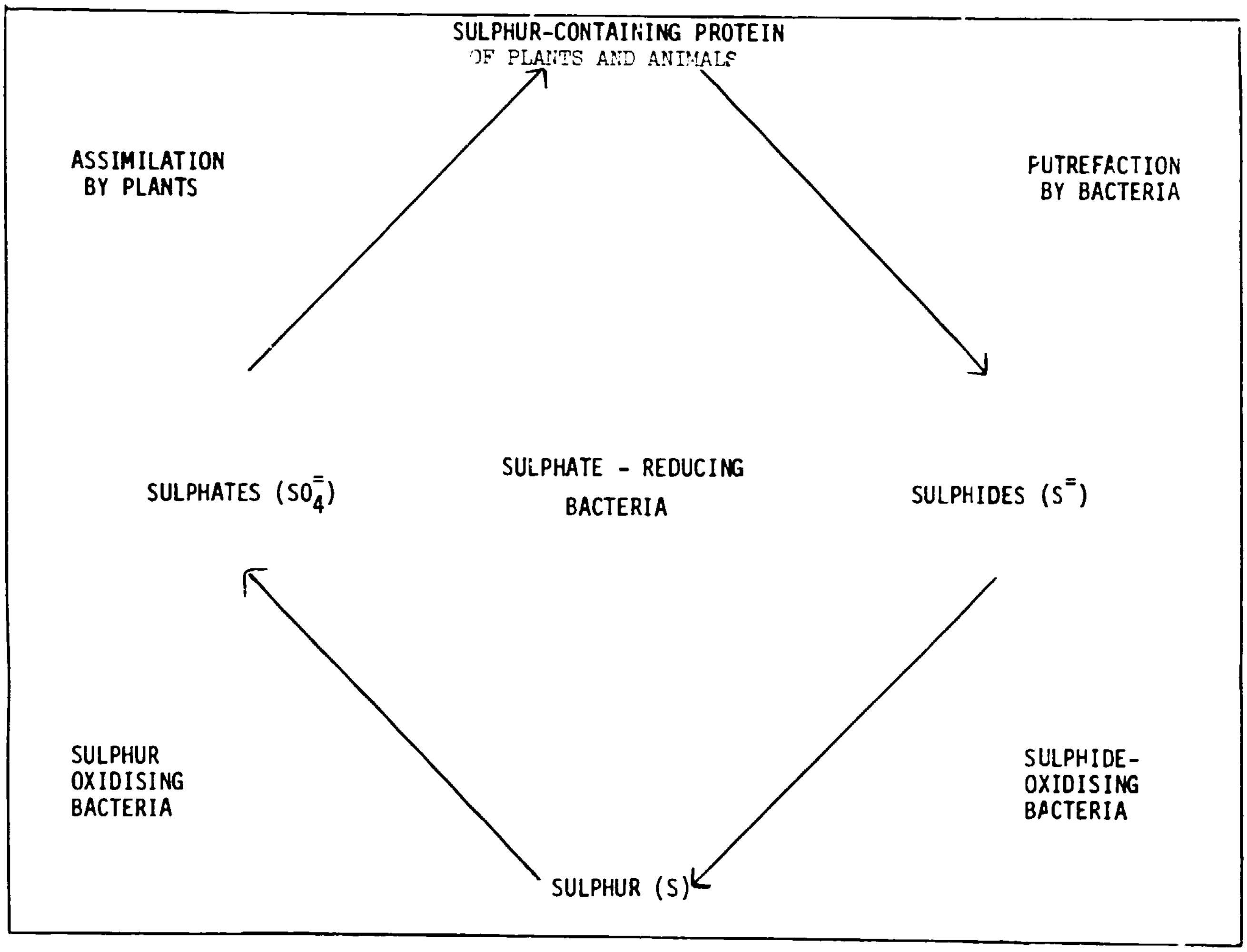
Constraints of space mean that only a brief account can be presented here. However, detailed references are given throughout the text, and these should be consulted alongside more general reviews. 29/ It also may be necessary to refer to the glossary of biological and technical terms which appears at the end of the present paper.

### 1.3.1 Microorganisms involved in bacterial leaching

Until the late 1970s, T. ferrooxidans was generally thought to be the only microorganism of significance in bacterial leaching. 30/ However, it has been demonstrated recently that mixed populations of bacteria, including thermophilic ones, may be more instrumental than pure cultures in effective mineral breakdown. 31/

Figure V

SULPHUR CYCLE




Source: I. J. Corrans, B. Harris and B. J. Ralph, "Bacterial leaching: an introduction to its application and a study of its mechanisms of operation", JSAIMM, March 1972, p. 222.

The types of organisms known to be involved are discussed below.

1.3.1.1 Thiobacillus ferrooxidans

This organism, discovered originally in drainage waters from a coal mine [32] is probably the most important and certainly the most studied bacterium involved in the natural leaching process. It is motile, aerobic, acidophilic, non-spore forming, single-pole flagellated, chemosynthetic, rod-shaped, and about 0.5 x 1.0 pm in size. [33] It is characterized by its ability to oxidize iron, sulphur, soluble and insoluble sulphides and compounds such as thiosulphate and tetrathionate. T. ferrooxidans utilizes energy derived from these catalytic oxidation processes for growth. Cell division is by binary fusion, and the time depends on conditions. It utilizes carbon dioxide as its sole source of carbon. It requires phosphates and other minor trace elements for chemosynthesis, as well as a source of nitrogen (usually ammonium) - although one strain of T. ferrooxidans can apparently fix nitrogen. [34] Its preferred temperature range is 20-35°C. The ability of T. ferrooxidans to utilize insoluble sulphide minerals, such as pyrite, chalcopyrite, chalcocite and covellite, as growth substrates accounts for its ubiquity in natural mineral leaching systems.

1.3.1.2 Thiobacillus thiooxidans

This organism is distinguished from T. ferrooxidans by its inability to oxidize iron or metal sulphides under most conditions. It grows on sulphur and some soluble sulphur compounds. It may have a role in the oxidation of sulphur generated in leaching systems, which in turn may enhance the activity of T. ferrooxidans through the ensuing exposure of fresh sulphide surface for leaching.

1.3.1.3 Leptospirillum ferrooxidans and mixed cultures of Acidophiles

There is now evidence that in natural and contrived leaching systems operating at temperatures below 35°C, mineral breakdown may also be due to the co-operative action of distinct species, including L. ferrooxidans, T. thiooxidans, T. organoparus, and T. acidophilus, rather than exclusively to the action of T. ferrooxidans. For example, mixed cultures of L. ferrooxidans and T. organoparus have been observed to grow on and degrade both pyrite and chalcopyrite which neither organism alone can metabolize. [35]

#### 1.3.1.4 Thermophilic thiobacilli

Several strain of bacteria - Thiobacillus TH1, TH2, TH3 and T. thermosulfidooxidans, isolated from thermal springs, natural leach dumps and test facilities - are capable of growing on pyrite and chalcopyrite substrates at temperatures around 55°C. 36/

The existence of bacteria distinct from T. ferrooxidans (as evidenced by different temperature optima and DNA composition) indicates that the selection from mutations to thermophily in that organism is only one of several areas in high temperature leaching which should be of interest to industry. 37/

#### 1.3.1.5 Extreme thermophilic bacteria

It has been demonstrated recently that several strains of spherical bacteria, capable of growth at temperatures up to 80°C, lacking cell walls, and resembling Sulfolobus acidocaldarius, are able to leach chalcopyrite and molybdenite (a valuable porphyry mineral) at 60°C, apparently more effectively than mesophilic bacteria. 38/ This may prove to be significant since temperatures in the interior of active leaching systems may reach 80°C as a result of chemical and biological reactions.

#### 1.3.1.6 Other bacteria

Other thiobacilli occurring in the leaching environment include T. delicatus, T. rubellus, T. thiparus, T. neapolitanus and T. novellus. 39/ They may be beneficial in the initial stages of leaching through lowering the pH content from the 4-7 range to the more acid 1-4 range, enabling the significant leaching organisms to function. 40/

Oxygen depletion can occur in leaching systems due to the high oxidative demands of the bacteria, and no truly anaerobic iron-oxidizing organisms are known to exist. 41/ However, T. ferrooxidans, T. thiooxidans and Sulfolobus acidocaldarius can couple the oxidation of sulphur with the reduction of ferric ions ($Fe^{+++}$) under anaerobic conditions, enabling sulphuric acid generation and sulphur removal to continue under oxygen-free conditions. 42/

### 1.3.2 The reactions of bacterial leaching

The overall process of bacterial leaching consists of a series of chemical and biological reactions of which only some involve bacteria although all influence each other. It is the failure to realize this that accounts for the suboptimal nature of industrial operations employing this technology since the scope for improving the process, through changing the living conditions and environment of the bacteria, is not exploited.

Bacterially-assisted leaching is usually described in terms of indirect attack via ferric ions ($Fe^{+++}$) and sulphuric acid, which can be generated by the bacterial oxidation of pyrite, soluble ferrous iron ($Fe^{++}$) and elemental sulphur, and a direct attack by the bacteria on the metal sulphides themselves. Although there are problems with this distinction, 43/ which can only be alluded to briefly here, the leaching reactions in each class are described below.

#### 1.3.2.1 Indirect attack

The leaching of copper sulphide minerals, unlike oxide minerals, cannot be completed in a sulphuric acid medium alone unless oxygen is present. The trivalent ferric ion however is an even more effective oxidizing agent. Since most copper porphyry deposits contain pyrite, the associated ferrous iron can be chemically oxidized to produce ferric sulphate - the active lixiviant. Chemically, this reaction occurs in air but is very slow. T. ferrooxidans bacteria, however, are able to oxidize ferrous iron at a rate $10^6$ times faster than this organic rate, if conditions favouring their growth exist.

So, in the leaching environment, ferrous sulphate, produced by the oxidation of pyrite:

$$FeS_2 + \frac{7}{2} O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4 \qquad [2]$$

or available in the leaching circuit after the cementation of copper:

$$Cu^{++} + Fe^{o} \quad Cu^{o} + Fe^{++} \qquad [3]$$

is oxidized to ferric sulphate by T. ferrooxidans:

$$2FeSO_4 + \frac{1}{2} O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O \qquad [4]$$

the T. ferrooxidans bacteria derive energy for their growth from the associated electron transfer.

The ferric sulphate then reacts with metallic sulphide minerals, leading to the solubilization of the metals, according to the general equation:

$$MS \text{ (metal sulphides)} + 2Fe^{3+} \rightarrow M^{2+} + 2Fe^{2+} + S^{o} \qquad [5]$$

The resultant reduced iron is then reoxidized biologically by T. ferrooxidans:

$$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O \qquad [6]$$

thus setting up an iron oxidation-reduction cycle.

Elemental sulphur is stable over a variety of conditions. However, sulphate is probably formed by some base metal sulphide oxidation:

$$MS + 8Fe^{3+} + 4H_2O \rightarrow M^{2+} + SO_4^{2-} + 8H^{+} + 8Fe^{2+} \qquad [7]$$

as well as by the oxidation, catalysed by T. ferrooxidans and/or T. thiooxidans, of the elemental sulphur formed in equation [5]:

$$S^{o} + {}^{1}/_{2}\, O_2 + H_2O \rightarrow H_2SO_4 \qquad [8]$$

This also contributes to the active lixiviant.

This reaction is important since the sulphur produced by equation [5] may form a passive layer on the mineral surface, which might prevent further ferric attack unless it was removed.

Specific equations for the oxidation, thus dissolution, of major sulphide minerals by ferric sulphate in order of decreasing reactivity (which is related to different crystal structures) include:

Chalcocite: $Cu_2S + 2Fe_2(SO_4)_3 \quad 4FeSO_4 + 2CuSo_4 + S^o$ [9]

Covellite: $CuS + Fe_2(SO_4)_3 \quad 2FeSO_4 + CuSO_4 + S^o$ [10]

Bornite: $CU_5FeS_4 + 6Fe_2(SO_4)_3 \quad 13FeSO_4 + 5CuSO_4 + 4S^o$ [11]

Sphalerite: $ZnS + Fe_2(SO_4)_3 \quad 2FeSO_4 + ZnSO_4 + S^o$ [12]

Pyrite: $FeS_2 + Fe_2(SO_4)_3 \quad 3FeSO_4 + 2S^o$ [13]

Chalcopyrite: $CuFeS_2 + 2Fe_2(SO_4)_3 \quad 5FeSO_4 + CuSO_4 + 2S^o$ [14]

Molybdenite: $MoS_2 + Fe_2(SO_4)_3 \quad 2FeSO_4 + MoSO_4 + 2S^o$ [15]

The bacteria therefore generate ferric ions which act as an oxidizing agent. This provides them with energy for growth and creates a suitably acid environment to maintain the oxidized metal species in solution.

1.3.2.2 Direct attack

Recent research suggests that bacteria can also catalyse the direct oxidation of metal sulphides by attacking the solid substrate. Some of this research is outlined below.

(1) Different corrosion patterns and reaction curves for pyrite and chalcopyrite leached in acid-ferric sulphate and acid-bacterial lixiviants indicate enhanced leaching rates with the bacterial solution. [44]

(2) Investigations have indicated that chalcocite and covellite substrates can be oxidized by T. ferrooxidans in the absence of iron, although the addition of iron to the system apparently increased solubilization rates. [45] However the interpretation of such results requires caution, since the presence of even trace amounts of iron in the mineral preparations could invalidate results;

(3) Electron microscope observations show physical attachment occurs selectively to sulphide phases rather than to the silicate matrix. 46/ Although, whether or not direct reaction with the surface occurs, it is clearly advantageous for the organism to be attached to the surface since it is then proximal to the oxidizable products of chemical leaching;

(4) Finally, there is evidence of bacterial oxidation of the sulphur moiety of mineral sulphides which contain iron, and ferrous iron itself in the crystal structure, independent of ferric ions. 47/

Specific reactions for major minerals include:

Chalcocite: $2Cu_2S + 5O_2 + 2H_2SO_4 \rightarrow 4CuSO_4 + 2H_2O$ [16]

Covellite: $CuS + 2O_2 \rightarrow CuSO_4$ [17]

Sphalerite: $ZnS + 2O_2 \rightarrow ZnSO_4$ [18]

Pyrite: $4FeS_2 + 15O_2 + 2H_2O \rightarrow 2Fe_2(SO_4)_3 + 2H_2SO_4$ [19]

Chalcopyrite: $4CuFeS_2 + 17O_2 + 2H_2SO_4 \rightarrow 4CuSO_4 + 2Fe_2(SO_4)_3 + 2H_2O$ [20]

Molybdenite: $2MoS_2 + 9O_2 + 6H_2O \rightarrow 2H_2MoO_4 + 4H_2SO_4$ [21]

The importance of explaining bacterial/substrate interactions stems from the necessity to understand their metabolism as a first step towards devising more effective methods for the dissolution of metals. For example, if it were the case that bacteria did not play a direct role in dissolving minerals, then the two stages of ferric ion generation and mineral leaching could be physically separated. This would enable the former process to operate at elevated temperatures unsuitable for bacterial growth, for example, in deep in situ mine situations. 48/ (This may be important in the leaching of uranite ($UO_2$), since the uranyl ion released during the oxidative reaction $U^{iv} \rightarrow U^{vi}$ is one of the few metals toxic at low concentrations to *T. ferrooxidans*. 49/

At present, however, the evidence suggests that in any leaching system where iron is present a combination of "direct" (i.e. $Fe^{3+}$ independent) and indirect (chemical and non-bacterial) attack can occur. The relative contribution of the two processes could depend on the type of minerals and bacteria, and the physical and chemical conditions of the leaching. 50/

### 1.3.3 Factors affecting bacterial leaching

Bacteria are living organisms. Therefore, the efficiency with which copper sulphides are reacted by ferric sulphate or direct catalysis will depend on environmental conditions as well as physical factors. The main factors affecting bacterial leaching are:

(a) Biomass yield;

(b) pH;

(c) Nutrients;

(d) Oxygen and carbon dioxide;

(e) Temperature;

(f) Light;

(g) Water potential, surface tension, wetting efficiency and pulp density;

(h) Particle size and surface area;

(i) Mineralogy;

(j) Galvanic effects;

(k) Metal tolerance and toxic effects;

(l) Interactive effects of the leach ecosystem.

Each of these will be discussed in turn. However, it must be emphasized first that every leach system will have its own set of peculiarities, in terms of mineralogy, types of organisms, solution chemistry etc., which will determine optimal conditions for bacteria activity in each situation.

(a) Biomass yield

To optimize leaching rates, and therefore metal recovery from sulphide minerals using bacteria, physical, chemical and biological conditions must be created which optimize their growth. Generally, the more thiobacilli there are the more lixiviant is produced, and thus the faster is the rate and the greater the efficiency of leaching. 51/ Even if leach systems are not innoculated, bacteria naturally present in porphyry deposits, or in the surrounding environment (ground, water, air), are observed to grow and multiply to levels suitable for sustained catalysis of the oxidation reactions.

One set of laboratory studies indicate that the bacteria volume required appears to be in the range of $10^5$-$10^8$ microorganisms per gram sample. 52/ While other researchers maintain that the bacteria usually find their own equilibrium which will depend on the conditions of the particular situation.

(b) pH

Optimum pH for leaching is in the range 1.9 to 2.8. In general, T. ferrooxidans are unable to start growing on ferrous iron if the pH is greater than 3, but once growth is initiated the pH can increase to 3.4. However, when the pH of the solution inside the leach system rises above 3, ferric ions may precipitate as ferric hyrdoxide. This may interfere with leaching, preventing air-water contact with coated mineral surfaces. The coating is difficult to redissolve, and the situation may be worsened if a pH rise of non-gravitational and capillary water causes ferric iron precipitation inside the particles. At a pH below 2.0, the rate of metal extraction has been observed to fall due to the suppression of bacterial metabolism. 53/

(c) Nutrients

Ammonium-nitrogen (most essential), phosphorous (for the first stage of energy metabolism), magnesium (necessary for carbon dioxide fixation), are the main nutrients required by the chemosynthetic bacteria. Thermophilic bacteria, however, seem to require organic supplements like yeast extract, sugar, glutathione or cysteine for growth on pyrite, chalcopyrite and covellite substrates. 54/

(d) Oxygen and carbon dioxide

The availability of oxygen is absolutely imperative for successful bacterial catalysis. 55/ Since bacterial leaching involves the oxidation of sulphide minerals, like chalcopyrite and pyrite, the chemical composition dictates that large amounts of oxygen must be available at the mineral surface - because two molecules of oxygen are required for each molecule of sulphur. 56/ Aeration is in part dependent upon interparticle pore space and leach system design, although air convection is naturally promoted by the heat generated by the oxidation of the sulphides present. 57/

Carbon dioxide availability is also essential since it provides the sole source of carbon for bacterial growth. The fact that carbon dioxide solubility is low in acid solutions may be a limiting factor on bacterial growth, if it falls much below levels normally found in air (0.03 per cent per volume). This aspect requires further research.

(e) Temperature

The most favourable temperature range for bacterial leaching is 20-35°C. By raising the temperature to 40°C the rate of oxidation of ferrous iron and of sulphides by T. ferrooxidans drops sharply, and at 45-50°C it ceases. Similarly, a temperature fall below 10°C inhibits reaction rates. However, recent research indicates that thermophilic bacteria can work at temperatures in excess of 45°C (see section 1.2.1).

Temperature fluctuation may also affect leach reactions, especially in small systems, and freezing and thawing have been observed to reduce bacterial activity.

(f) Light

Direct sunlight has an inhibitory effect on bacterial activity, although particulates and ferric iron may offer some protection. 58/

(g) Water potential, surface tension, wetting efficiency and pulp density

Water is an essential input to the leaching process, as a carrier of both the oxygen and carbon dioxide required by the bacteria and the metal sulphates produced. However, in excess it can reduce pH. Adequate drainage and flow regulation are therefore required. It has been observed that T. ferrooxidans are able to grow and oxidize iron at water potentials (free energy difference between the system under study and pure water) of between $-1.5 \times 10^6$ Pd * and $-2 \times 10^6$ Pd (-15 to -20 bars), and that some environments otherwise suitable for T. ferooxidans growth have water potentials too low for the organism. Reagents like glycerol or sodium chloride may be used to obtain correct water potential, though they themselves may inhibit bacterial action. 59/

Furthermore, one study showed that organic solvents left in the leach circuit after solvent extraction may decrease the surface tension of the leach liquor, and diminish the ability of T. ferrooxidans to leach chalcopyrite by interferring with growth and nutrient uptake and discouraging attachment. 60/

Finally, the speed of bacterial oxidation of sulphide minerals in part depends on the ratio of particle volume to solution. Therefore, too much solid reduces space for bacterial growth and leads to particle sedimentation, a build up of precipitates and thus a reduced surface area for sulphide oxidation reactions. 61/

(h) Particle size and surface area

Particle size is considered to be one of the most important factors affecting bacterial leaching.

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* Pd - potential difference.

In general, the smaller the particles the greater the leaching rate, since a greater surface area is exposed. 62/ Large boulders or areas of unfractured rock mean that much of the mineral content is unavailable for leaching; on the other hand, too small and too evenly distributed particles may clog solution channels and reduce the aeration of the system. 63/ It has also been observed that particle size of the host rock can significantly influence the leaching process, since gangue surface will be increased as well as the available sulphide mineralization. 64/

(i) Mineralogy

a. Primary mineral effects

Copper minerals can be categorized according to their resistance to leaching (e.g. see section 1.2.2). For example, chalcopyrite, which is a common porphyry sulphide mineral, is known to be the most recalcitrant. Leaching rates and the quality and amount of copper that can be recovered are therefore constrained by the original mineralogy. Gangue minerals may also influence leaching by exhibiting a buffering capacity, acting as a cation or anion absorbent and affecting water potential. 65/ More serious is the problem of acid consumption by gangue.

Although copper porphyries are found in igneous host rocks, acid-consuming carbonates or clays are often present. Associated reactions may lead to a raising of pH and concomitant problems of iron salts precipitation.

b. Secondary mineral formation

The effect of pH on mineral precipitation and the formation of sulphur coatings has been discussed already. Iron, if present in high concentrations in solution, may precipitate causing blockage or binding of the ore particle, limiting leaching.

Jarosite has also been observed to precipitate. This may also cause the leach solution to become depleted of cations such as potassium, sodium and ammonium, all necessary for the growth of chemoautotrophic bacteria. A reducing solution like sodium bisulphite may need to be passed through the system. 66/

If leach systems are left dormant, copper sulphate crystals may form which may enhance metal dissolution in the next leach phase after a prior rest period.

(j) Galvanic effects

Many copper deposits are characterized by separate disseminated inclusions of pyrite and copper minerals. In these situations, pyrite normally reacts much faster than chalcopyrite. However, it has been demonstrated that when these two minerals are in intimate (electrical) contact, chalcopyrite reacts more vigorously and the pyrite is passivated and only copper is released into solution. 67/

(k) Metal tolerance and toxic effects

T. ferrooxidans has a high tolerance to metals compared with most other microorganisms, although heavy metals tolerance varies with different strains of T. ferrooxidans and is related to adaptation to the environment. 68/ Mercury, silver and uranium in their elemental form are considered to be very toxic to thiobacilli, and molybdenum may be inhibitory; although some strains can adapt to it. This is particularly relevant to the Andean copper porphyry zone in which molybdenum is found as a by-product. Local bacteria will probably have adapted to it and will therefore be much more likely to demonstrate higher leaching abilities than foreign bacteria.

It has been noted that in the presence of metals, T. ferrooxidans exhibit a lag period before iron oxidation begins which has been interpreted as a selection phase in which only tolerant strains survive. It also seems that heavy metals appear less toxic in an acidic environment. This indicates the advantage of using local acidified mine water in the leach system.

(l) Interactive effects of the leach ecosystem

Only very recently has the complexity of a natural leaching environment been recognized. Researchers have reported that certain heterotrophs may destroy thiobacilli and interfere with the leaching process by plugging channels to solution flow, altering solution properties and coating surfaces preventing access for reaction. 69/

There are a variety of microbes and microflora that thrive within the limits of life-sustaining environments (pH 2-3, temperatures 20-85°C). Many appear mutually beneficial (see section 1.2.1). Recent research indicates a mutual relationship between T. ferrooxidans and acid-tolerant strains of nitrogen-fixing Beijerinckia lacticogenes; the former providing organic carbon and the latter nitrogen compounds. 70/

Microbes and microflora may also play an important role in the weathering of rock. This would expose new surface areas for reaction and enable lixiviant to intrude into particle cracks. 71/

The preceding discussion indicates that under certain conditions the microorganisms involved in bacterial leaching become less viable and oxidation reactions decline. This would be detectable in solution effluent since the percentage of contained metal would be reduced. So, although bacterial leaching is a natural process its efficiency can be clearly improved either in its existing system or through the construction of systems according to the conditions considered optimal for the particular ore being treated and bacteria and mine water employed.

However, even from this brief outline it will be clear that the factors affecting bacterial leaching are not only numerous and complex but also interactive and dynamic. Much of the research discussed above is in its infancy * and personal communications with world experts on the subject indicate that there is still a paucity of knowledge about the fundamental controlling conditions of the leach system. **

Furthermore, the capabilities required to identify and obtain optimum conditions in a laboratory are much less complex and extensive than those required to scale up the whole leach system into an efficiently working commercial plant - particularly since the leach cycle is measured in years rather than weeks. It is to scaling up and the associated problems involved in optimizing industrial operations that the discussion now turns.

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* See section 1.4.3. for further discussion of areas which particularly require more research.

** For helpful comments, the author is indebted to N.W. Le Roux of Warren Springs Laboratory, the Department of Industry, the United Kingdom and A. Bruynesteyn of the British Columbia Research Council, Canada.

## 1.4 Leach system design and optimization

Economically, bacterial leaching is an important method for extracting some metals from their ores. As noted before, more than 10 per cent of the copper produced in the United States is derived from this source. However, industrial operations such as these have been run mainly by chemical engineers with minimal knowledge of microbiology, while most of the microbiological research has been carried out in research institutes or universities by microbiologists with little focus on the engineering problems associated with industrial application. This dichotomy reveals itself in the inadequate treatment of leach system design and optimization in the literature, and the inefficiency of practical commercial leaching operations.

E.E. Malouf, J.D. Prater and J.T. Woodcock were the first to discuss the need to study leach regimes. 72/ Very soon the Kennecott Copper Corporation took up the challenge and became a leader in dump leaching and solution mining research. The 1970s witnessed increasing attention being paid to the systematic leaching of low grade waste in the United States which, by 1980, was accumulating in areas surrounding the open pit copper porphyry mines of the south west at a rate of 1 million tons daily. In fact, 60 per cent of the local United States copper production from leaching is obtained from leaching waste rock and overburden from the mines in this region. 73/ Again, this illustrates the fundamental link between geology and mineral technology.

Kennecott's leach dumps at Bingham Canyon, Utah (apparently the largest in the world) contain over 2,000 m tons of rock.

Elsewhere in the United States, large dump operations exist in Nevada, Utah, Montana, Arizona and New Mexico, while heap and in situ operations are mainly in Arizona and Nevada. 74/ Other operations outside the United States are located in Australia, Bulgaria, Japan, Mexico, Portugal, Spain, the Soviet Union, Zambia and of course Peru. The salient characteristics of the principal dump leaching operations in the world are summarized in annex I.

The vast reserves of copper in waste dumps, the low recovery rates and long periods of operations have been limited by poor dump design and layout coupled with a lack of knowledge about leaching mechanisms. This is in part a consequence of lack of planning and preparation. It must be emphasized that dumps leach naturally and are not necessarily constructed to facilitate the recovery of copper from their effluent. Only recently has it been realized that bacterial leaching is not simply a case of extracting copper from a natural process, but that the efficiency, and thus economic viability, of a leaching operation can be profoundly influenced by human intervention or, in other words, technical charge. This has resulted in efforts being made in the experimental assessment and process modelling of industrial-scale leaching systems although, as yet, the microbial aspects have remained largely unexplored.

In this section, a typical leaching system design is outlined and then, in the light of the discussion of the previous section, the ways in which the process may be optimized will be examined.

### 1.4.1 Leach system design

Waste, or marginal ore, is usually carried the shortest possible haul from the open pit to the dump site. Minimum secondary breaking is done to cut down costs so the dump may contain huge boulders, perhaps containing inaccessible minerals. Depending on how the mine is worked and the local topography and geology, the dumps may be large or small, on hillsides, in valleys or on gently sloping land. Material is usually dumped from the top edge so the dump is built as a series of thin sloping layers. Two effects of this are that the top few metres of successive layers are compacted by trucks (interfering with percolation), and there is a tendency for boulders to roll down the slope. In some dumps this may provide voids for aeration and facilitate effluent collection. For efficient solution recovery, the dump should be on a sloping impervious site from which the effluent can gravitate to one or two collecting points.

A general plant layout is illustrated in figure VI. It consists of dump, storage capacity for dump effluent and precipitation tailings, the metal recovery plant itself, and various pumps and solution lines.

All materials of construction must be capable of withstanding the attack of warm dilute ferric and sulphuric acid solutions containing numerous metal ions.

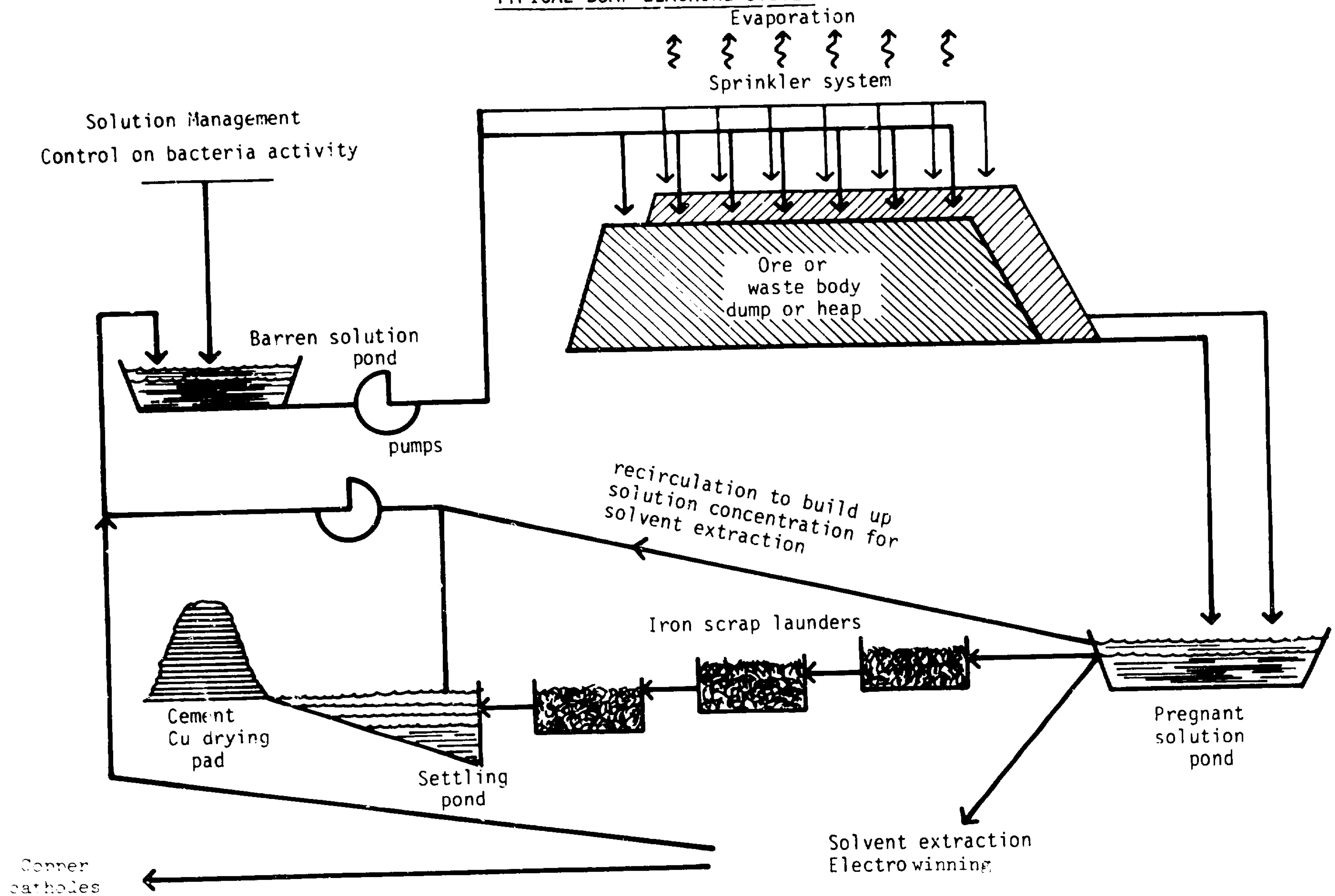
Storage tanks generally need to have capacities ranging up to 20 metric gallons. They are usually built with rock, earth or concrete and may be lined internally with aluminium-coated polyvinyl plastic sheet, hypolene, or sealed with Gunite, bitumen or clay. Pumps are usually made of special grade stainless steel and pipes, which may be up to 35 cm in diameter, may be of steel lined with cement, asbestos, fibreglass, PVC, epoxy resin or wood.

Preparation for the application of leach solution may involve bulldozing the surface to loosen it before the first application, or after the heap has lain dormant to break up ferric hydroxide precipitation. Solution is then run out along channels and is delivered either from a branch line from the main distribution line, from a series of holes in a branch line, or through simple sprinklers.

Dump permeability, usually varies from 1.5 $kl/m^2$ per day for dumps older than 30 years containing slimes, to 12 $kl/m^2$ per day for younger dumps not yet consolidated. The more acid the solution is the greater the permeability. [75/] The time taken for percolation varies from a few hours for shallow dumps to a month for larger dumps more than 150 m high. There is no general rate or optimum rate for copper extraction since rates will vary for each leach system. However, it may take up to a year to reach the desired rate of extraction, and several years to deplete the heap of its accessible copper content. If solvent extraction is to be employed, recirculation of the effluents may be necessary to raise the copper content to the minimum 1.5-2 grams per litre required for solvent extraction.

Figure VI

TYPICAL DUMP LEACHING SYSTEM




Source: L. E. Murr, "Theory and practice of copper sulphide leaching in dumps and in situ", Minerals Science and Engineering, vol. 12, no. 3 (July 1980).

The solution is then collected at the base of the dump and is pumped (or flows by gravity) to the metal recovery plant. This is located at a convenient site for intake and discharge of water and lixiviant where, for example, iron can be brought in and cement copper taken out. Barren solution (see section 1.3.2.1, equation [3]) is then pumped back up to the top of the dump and recycled through the system.

1.4.2 Optimizing the leach system

It should be clear from the discussion in section 1.3.3 that the optimization of the leach cycle for dumps and heaps could occur in a number of ways and at a number of points in a circuit outlined immediately above. Given that the rate of copper sulphide leaching is principally controlled by (a) the rate of bacterial conversion of ferrous to ferric iron, (b) the rate of sulphide oxidation by ferric iron and direct bacterial attack, (c) the rate of air convection, optimization can proceed along three interconnected paths. These are first, through solution management; secondly, through improved system design; and thirdly, through making adjustments to the bacterial population and by changing conditions to increase bacterial efficiency.

Since the primary aim of a commercial leaching operation is to obtain a maximum yield of metal from the ore in a minimum amount of time, preliminary geological evaluation and an assessment of ore leachability is essential. The discussion will thus deal first with these two tasks.

1.4.2.1 Geological evaluation

The first stage therefore involves making an estimation of the tonnage and grade of the minerals in the heap. This could be done by the technique of ore assaying. This involves sampling the material, digestion by sulphuric and nitric acid, pulverization and then analysis of metal content by atomic absorption and spectrometry. It is easier to estimate the copper content of heaps since the coring of the overburden can be carried out before mining at regular spatial intervals, and stringent cut-off criteria can be applied.

In the case of dumps it is difficult to devise a reliable selection and measuring technique since it is not economically feasible to open them up and their unconsolidated nature leads to sample contamination. Samples should be obtained from as deep inside the dump as possible - not just from the surface - since mineral of high grade is likely to be buried deepest. Assumed mineral contents on the basis of past cut-off grades or knowledge of the grade of ore before mining, which is how most dumps have been assessed, is not sufficiently reliable. This is because it is important to ascertain the exact percentage of copper content before starting operations so that the leach cycle can be determined and a rate of economic remuneration established. If the copper content of the effluent declines, it is essential to be able to determine whether this is due to the depletion of all accessible copper, blocking by fines or precipitations or to the deterioration of conditions favourable for bacterial activity. Unless the reasons are known an informed decision cannot be taken as to whether or not the operation should be terminated or the leaching parameters corrected.

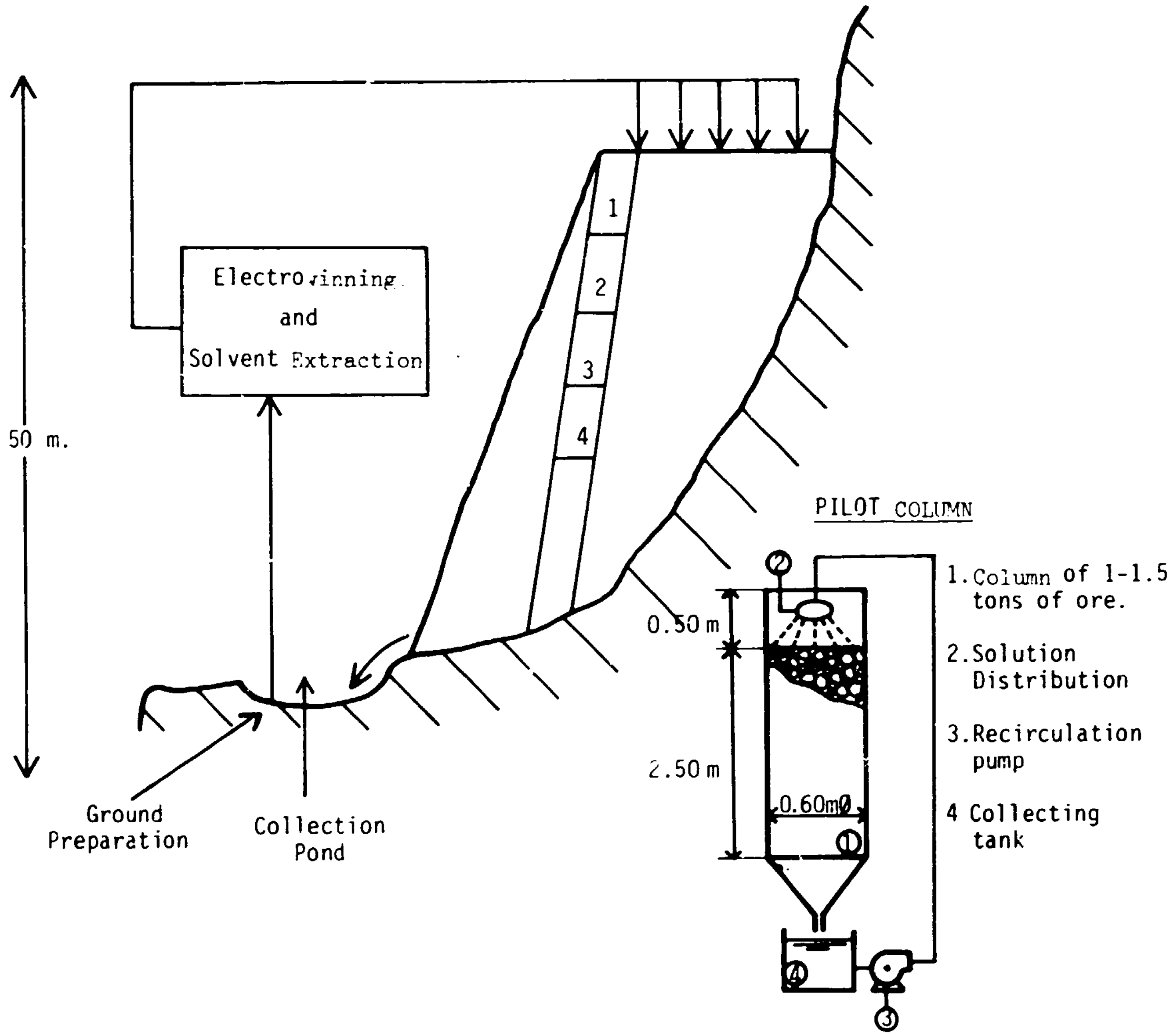
### 1.4.2.2 Assessing leachability of the ore

The next stage involves testing the leachability of the ores. A. Bruynesteyn and D.W. Duncan suggest a two-phase evaluation programme. 76/ It consists of an inexpensive and rapid shakeflask test followed by more extensive column tests to study the feasibility and optimum conditions for the proposed commercial leaching system. First, small quantities of a representative sample are finely ground and leached under ideal conditions. Results show in one to two weeks. By comparing the rate and extent of extraction obtained with those of other mineral samples with known commercial characteristics, a decision can be made about moving on to the second phase. Obviously, if little or no extraction is achieved or if acid consumption is excessive, economic extraction in commercial heaps consisting of larger particles would not be feasible.

Samples exhibiting promising leaching characteristics may then be subjected to column tests. These are designed to closely resemble the proposed commercial operational conditions (see figure VII). The carrying out of these tests requires close co-operation with the technical operations division of the mine. A. Bruynesteyn and D.W. Duncan describe the design of leach columns of 1-2 tonne capacity. Each column is equipped with a small can precipitation plant, so that dissolved copper can be recovered and exchanged

Figure VII

RELATION BETWEEN A COLUMN OPERATION AND AN INDUSTRIAL-SCALE LEACH DUMP




SOURCE: E. Oak, "Lixivación bacterial de minerales en pila/botadero" a paper presented at the International Symposium on the Current Technology of Copper, held at Bucaramanga, Colombia, in December 1982.

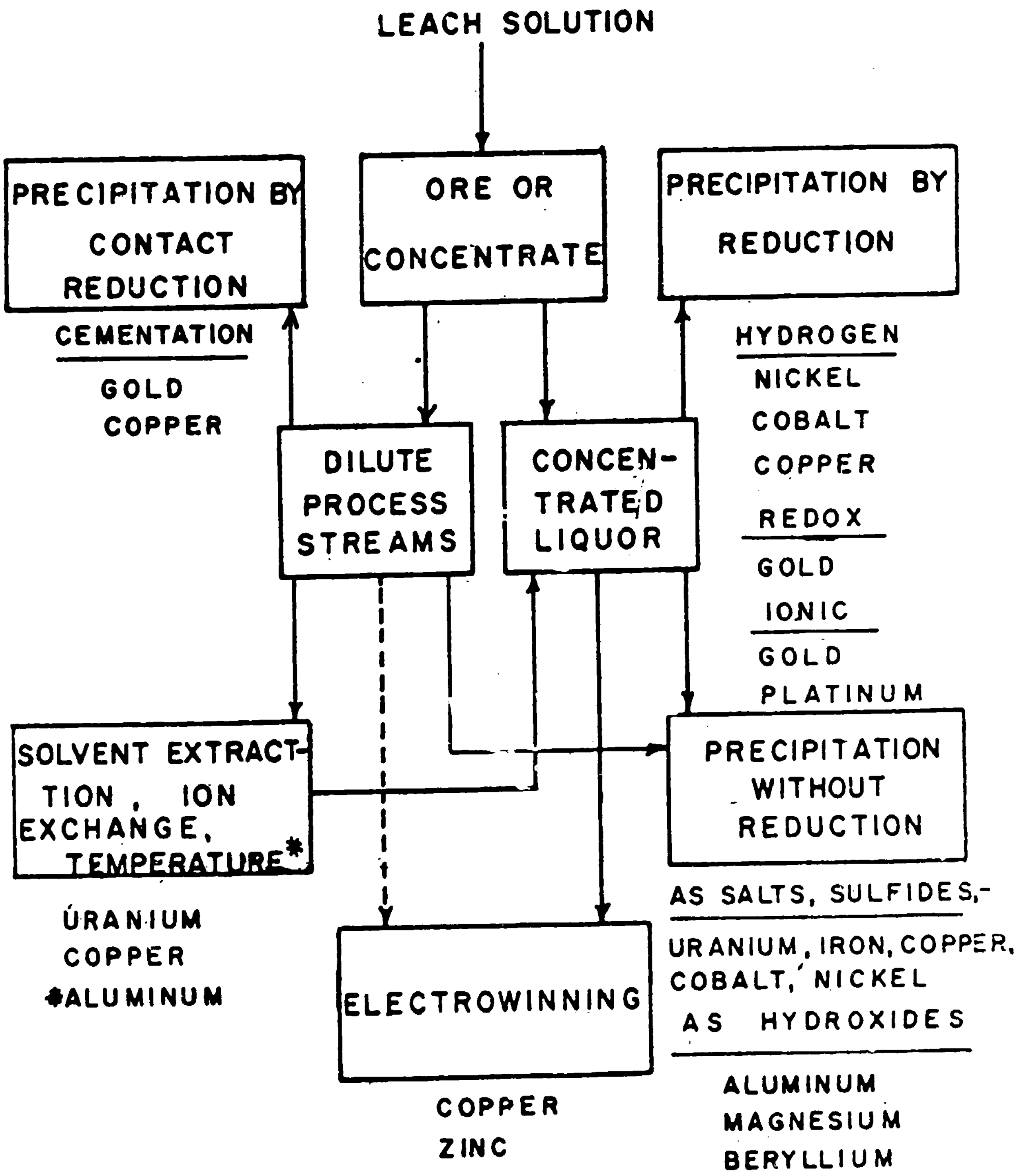
or ferrous iron. The barren solution from the precipitation plant is then recycled to the top of the column, thus simulating commercial conditions. By frequently sampling and assaying small amounts of the percolating leach solutions at 3 m depth intervals, it is possible to analyse changes in the leach solution as it percolates down through the ore, and changes in the solution and particle characteristics over time. This will yield important data which can be used to optimize the commercial leaching operation and inform management on the economics of potential industrial application. For example, column leaching may reveal tendencies of fines formation, acid-consuming gangue or the existence of previously unrecognized galvanic effects which may markedly enhance the process's economic prospects. Furthermore, at this stage it is possible to analyse the effluent solutions to determine the extent to which other minerals have been taken into solution. Methods of metal separation and recovery may then be devised since the economic viability of the overall process may depend on the recovery of by-products such as gold or cobalt (see figure VIII).

Finally when evaluating the leachability of a given ore an important step is evaluating the microbiological characteristics of the ore and its environment. This, however, is neither mentioned in Bruynesteyn and Duncan's programmes nor usually carried out during the process route selection stage. This would involve collecting mine water samples from either the mine itself or the dumps and analysing their biological and chemical characteristics in their natural state. This requires identifying and counting the bacteria present and determining pH and $Fe^{3+}$ and toxic metals content - all of which would be indicators of the extent to which bacterial leaching could be expected to take place. Such testing must be carried out at the mine site since the biological characteristics of the mine water change with transportation, particularly if there are temperature and altitude differences involved.

After this, optimization can then proceed along the three interconnected paths mentioned above. Each of these will be discussed in turn.

FIGURE VIII

METHODS OF MINERAL SEPARATION




SOURCE: A. Bruynesteyn and D. W. Duncan, "Biological leaching of sulphide ores", a paper presented at a Conference on Means of Exploiting Low Grade Ores, held at the United Nations, New York, in 1972.

1.4.2.3 Solution management

For a specific leaching operation, solution management may involve working on process optima such as lixiviant application rate and mode, onfluent pH and ion concentration, percolation rate and wetting efficiency.

Oxygen is brought to the mineral surface by diffusional processes. It is therefore necessary to maintain the thinnest possible water layer around the mineral particles in order to create the least diffusional barrier for the transport of the oxygen. 77/

Although it is difficult to create these conditions in the heap or dump situation, leaching has been observed to proceed fastest while the system is dormant and minimal amounts of gravitational water are present. The extent of this "rest period" before wetting should be determined by the rate of evaporation and the associated concentration of salts observed in the remaining liquid phase around the particles.

This wetting should be considered a washing cycle to remove the metal sulphates (e.g. crystallized copper sulphate) produced during the preceding rest period. Some researchers also recommend cyclic wetting, emphasizing that the interval between solution application (dump flushes), as well as the duration of specific flushes (irrigations), should be worked out for each individual system. 78/

High leach rates or rates of solution application are normally not efficient since they unnecessarily dilute the copper values and iron in the solution. However, in very large dumps or heaps, which may build up excess heat due to limits on heat expulsion, and high rates of solution application, short rest periods may result in a beneficial reduction of temperature. While too much cold solution may reduce temperature and cause reaction rates to decline. 79/ Empirical evidence indicates that rest periods should be roughly twice the duration of application, and that the application should not exceed more than one week, 48-96 hours appearing to be the optimum. 80/ This procedure of cyclic wetting may be only feasible, however, when the total sulphide content of the ore is sufficent to allow biological acid production to exceed the acid consumption of the gangue; otherwise, the pH of the liquid phase will rise, causing the formation of insoluble ferric hydroxide (see section 1.3.3 (b)). 81/

As regards the optimum water composition, research indicates that acidified fresh water is not suitable for leaching. To initiate leaching, it is necessary to obtain bacterial levels of about $10^4$ - $10^5$ cells/cc, as well as iron (mainly $Fe^{2+}$) in solution to levels of approximately 0.4g/l. 82/ In practice this also limits pH to below about 2.6, which is within the optimum range for bacterial catalysis and which also discourages iron hydroxide or jarosite precipitation. It is therefore advantageous to begin the leaching of a new regime with tailings or mine waters or other leach lixiviants which conform to these figures - especially since the local leaching bacteria will be adapted to the dissolved mineral composition of the mine water which will make them more resistant in their new leaching environment. Furthermore, given the inhibitory effect on bacterial activity of light [1.3.3.(f)], it may be beneficial to apply solutions during the night and to ensure solution storage tanks and redistribution systems are kept in obscurity.

As was emphasized in section 1.3.3 the pH-controlled iron salt precipitates exert a high degree of control over the efficiency of the leaching process. However, it is difficult to change pH in the fully scaled-up situation; it is expensive to add sulphuric acid, and it is practically impossible to break up precipitations deep inside the system. A major requirement then in any leach operation is constant control over solution characteristics like pH and bacterial volume which requires a sort of "preventive maintenance" approach rather than a "trouble-shooting" one. Therefore, a mobile laboratory and technical team at the mine site may be vital to the optimal functioning of the leaching system.

### 1.4.2.4 Optimizing system design

In most practical applications of leaching, oxygen availability is one of the critical parameters of the leaching process. The method of leach solution application to the surface of the dump, the amount of fines present or extent of precipitates, particle size and compactness, as well as overall system height and shape, influence the amount of oxygen which is able to penetrate into the dump.

Solution should be sprayed onto the heap so that each droplet will draw oxygen down with it as it begins percolating through the heap.

Many leach dumps, by virtue of their mode of construction, contain numerous layers of fines, either in horizontal planes or at $39^{\circ}$ angles. Such layers apparently filter out further fines from the percolating leach solution and very quickly become impervious to both water and air. The amount of fines produced may be a function of the amount of extraction obtained and particle decrepitation. Therefore, any leach heap constructed of materials prone to significant fines production (this can be evaluated during column testing) must be kept shallow. Blasting or "dump fluffing" apparently causes a decrease, and not the desired increase, in permeability. 83/

The mineralogy of the ore will also place constraints on optimum heap design. Since a great deal of exothermic heat is generated by the oxidation of pyrite, it is not advisable to have too much pyrite present. Although in practice the selecting of material for heap construction is usually an unacceptable additional cost, material containing a high percentage of pyrite could be built into smaller heaps; exposing as much surface area as possible for cooling, or extending rest (i.e. cooling) periods, could be taken into consideration.

In general, increasing the size or height of a heap will reduce reaction rates by creating excessive temperatures for most bacterial activity. This will cause a decline in acid production, a rise in pH, and lead to a precipitation of iron salts (see above). Large heap volumes will also reduce air convection, causing reactions to starve and jarosites to precipitate. Taking all these factors into account, R.S. Shoemaker, R.M. Darrah, L.M. Cathles and W.J. Schlitt have all concluded that optimum heap dimensions should be approximately 15 m high and 30 m wide. 84/ Long, finger-like sections with these dimensions could be constructed. Existing dump efficiency might also be improved by partitions to achieve sections of this size. However, it must be emphasized that there is no general rule, and each system design must be based on laboratory evaluation of the material to be leached and an investigation of the geography of the environment as well as the microbiology. For example, high up in mountainous areas, leaching dumps may create a massive chimney effect, drawing cold air into the heap and generating huge updraughts. Indeed, oxygen ingess would probably be greater in winter in such areas.

Ideally, the location of the heap should be on fairly flat or gently sloping ground to facilitate construction, design and effluent collection. To optimize recovery and reduce solution loss, the base of the heap should be constructed on an impervious, artificial (e.g. PVC) or geological (e.g. clay) layer.

Particle size is an important constraint on leaching (see section 1.3.3); however, to optimize particle size and distribution for a particular heap is a difficult and potentially expensive operation. Rock type primarily determines particle size and after shattering, a decision has to be made concerning the economic trade-offs associated with further crushing to increase the surface area for more efficient leaching. If particles shatter too small then the addition of larger particles to enhance aeration and solution percolation must be considered.

#### 1.4.2.5 Bacterial populations and genetic improvements

The third path to optimizing the leaching process involves the bacterial population itself. For optimal bacterial activity, oxygen must be supplied to the heap, an acid pH must be maintained and excessive temperatures avoided. The required nutrients generally exist within the material of the natural leach system (that is their natural environment) anyway; although an analysis should be made and absent nutrients added.

In general, dump leaching systems currently operate with the natural populations of organisms already existing in the ore. These will be best adapted to the environment; for example, they will have developed, where necessary, tolerance to various locally occurring metallic substances. Apparently, introducing a genetically "marked" strain of *T. ferrooxidans* did not increase leaching, although repeated inoculation of the dumps with the strain over two years led to 55 per cent of the detectable *T. ferrooxidans* exhibiting the genetic marker. [85/] Other researchers argue that any inoculation of selected strains into a natural leaching environment is unlikely to be successful, since the leach system would be bound to revert back to its natural ecosystem balance. In deep solution mining of disintegrated ores or in newly constructed heaps, however, it may be necessary and advantageous to inoculate the system with suitable strains if optimum bacterial activity is desired.

Similarly, it may prove beneficial to inoculate unnaturally created hot regions with thermophilic bacteria and to employ mixed cultures (rather than pure ones) native to the material used. In section 1.3.1.3 the potential mutualism between T. ferrooxidans and the nitrogen-fixing Beijerinckia lacticogenes was noted. If nitrogen was being provided in this way, it would not be necessary to add ammonium to the leach system, which in turn would limit the undesirable formation of jarosite. However, it is very expensive to add nutrients, and each case warrants an economic trade-off to determine the relative benefits of such an investment.

Nevertheless, it is possible to outline areas where current research is in progress and where improvements to the bacterial input to leaching could be made in the future. These are discussed below.

(a) Increasing the rate of the oxidation process of ferrous to ferric

It was demonstrated that ferric ions, which are the main oxidizing agent in bacterial leaching, are regenerated by the microorganisms via the reoxidation of the ferrous ions produced (section 1.3.2.1, equation [6]). This reoxidation process is one of the rate-limiting steps of mineral leaching, since the ferric ions competitively inhibit the rate of ferrous ion oxidation. It has been shown that ferric sulphate affects the growth of T. ferrooxidans because of its inhibitory effect on the ferrous ion oxidation. It would therefore be desirable to obtain a mutant of T. ferrooxidans for which the oxidation step would not be repressed by ferric sulphate.

(b) Enhanced, or selective, oxidation of specific minerals

A much purer end-product would be created if microorganisms could be engineered so that only specified minerals were taken into solution.

A.M. Chakrabarty has suggested the introduction of plasmids, specifying resistance to metal ions such as silver, mercury, cadmium etc., to *T. ferrooxidans* mutants. [86/] Other researchers refer to the potential for strain improvement by the selective development of multiple metal tolerance. [87/] Plasmids are also known which can increase the resistance of host cells to ultraviolet radiation. These could be introduced into *T. ferrooxidans* cells, thus protecting them from the killing action of ultraviolet or X-rays. [88/]

(c) Self-generation of nitrogenous nutrients

The advantages of the self-generation of nitrogenous nutrients was noted in section 1.3.1.3 and 1.3.3. Since *T. ferrooxidans* is a gram negative short rod-shaped bacterium, Chakrabarty suggests that it may be possible to introduce plasmids of Pl-incompatibility groups such as RP4 into it. RP4 plasmids could apparently be transmissible and stably maintained in *T. ferrooxidans*, and may lead to their being able to fix nitrogen.

However, little work has been done to seek improvement of practical leaching systems by genetic manipulation of organisms. Firms apparently involved in such research include Imperial Chemical Industries and Biogen. There are many problems associated with such research, including the small growth yields available on ferrous iron, the difficulty of using solid substrates (e.g. pyrite) in genetic techniques such as replica plating, the difficulty in certain cases of obtaining growth of single colonies on solidified media and the difficulty of working with bacteria (including the simple action of counting them in an acid medium). [89/]

It is absolutely essential to emphasize that advances in the field of genetic engineering of leaching bacteria are dependent upon a detailed understanding of the physiology and biochemistry of the organisms involved. And there is still a lot of fundamental work to be done in that area, as the review presented in section 1.3.1 suggests. Furthermore, the bacterial leaching of minerals has not been given sufficient treatment, compared with other microbial processes, in the biotechnology literature. Usually it is simply mentioned by name as a possible application. Since bacterial leaching has not yet been located in the biotechnology context it may be beneficial to explore existing research and facilities in the area of genetic engineering and strain improvement of thiobacilli-like bacteria to see to what extent there are common theoretical bases or research procedures. This is in fact taking place in Chile where the universities are planning an extension of their microbial and genetic research programmes to include leaching bacteria. This move is related to the fact that the country's mining companies, especially CODELCO, are developing large projects in the areas of the bacterial leaching of marginal ore.

Finally, and this is a comment which is relevant to the whole issue of process optimization, improving a leach system is usually an added cost to a conventional mining and mineral processing operation. The discussion above indicates that at every stage, beginning with the decision to carry out a geological evaluation and the initial dumping, an economic decision has to be made concerning the trade-offs between the economic remuneration likely to result from recovering the contained copper, and the cost of designing the process route in order to do this in the most efficient way possible. Such trade-offs are obviously affected by the tonnage of copper likely to be recovered, the length of the required leaching cycle and the overall economics of the whole mining and mineral processing operation. Therefore, a prerequisite to the expenditure of any funds on the design and development of an industrial leaching process should be laboratory evaluation and scale tests to assess the leachability of the material and its likely behaviour under commercial conditions. While such evaluations can be carried out by the firm, including the preliminary microbial analyses, a bacteria optimization and genetic engineering programme is beyond the scope of the sphere of a national mining company's operations. This implies an increasing role for the national research institutes and universities.

The importance of building up local centres of expertise rather than relying on foreign centres is related to the necessity to use bacteria and mine water from the mine site of application (since the main requirements of bacteria for growth will be best fulfilled by their indigenous environment and they will be well adapted to the elements and nutrients dissolved in the local mine water), the constraints on sample transportation, and the necessity to refer back continuously to the site of origin and application during ongoing research. This trend of localization is evident in both the Peruvian and Chilean cases of technology development in the area of bacterial leaching.

Currently, then, the main ways in which a bacterial leaching operation can be improved are through adequate solution management and careful system design. This ensures a high rate of aeration, the maintenance of highly acidic conditions and the frequent percolation of lixiviant over as much sulphide surface area as possible. This in turn enables the microorganisms indigenous to the particular leaching environment to assist and stimulate oxidation reactions and thus to maximize the amount of metal taken into solution and minimize the time required to do so.

Microbiological optimization is currently achieved only in a limited way and essentially indirectly. This is considered to be due to the failure to recognize the importance of the microbiological components of the leaching process; and is related to the fact that most commercial operations are large dump systems which do not warrant redesigning and already have their own vibrant populations of bacteria. However until independent efforts are made to accelerate the bacterial activity, and systems are designed with this as a guiding objective, the operation of any leach system will probably be sub-optimal.

### 1.4.3 Areas requiring further research

In conclusion, it is evident from the discussion in both sections 1.3 and 1.4 that further research, engineering work and information diffusion is necessary before the economic viability of the widespread application of bacterial leaching can be determined. The areas which require more study are listed for reference below:

(a) The fundamental biology of the main leaching organisms and their role in catalysing oxidation reactions; in particular, the extent to which mineral sulphides can be directly attacked by bacteria;

(b) The extent to which enhanced strain or genetic engineering can improve leaching organisms and can be successfully applied in commercial systems;

(c) The relative importance and interactive effects of mixed cultures of microorganisms on the leaching process; in particular, the potential contribution that can be made by high temperature bacteria;

(d) Natural bacteria behaviour patterns in large leaching systems like heaps, dumps and old mine workings;

(e) The controlling influence of initial mineralogy, and related possibilities for adding material to the system;

(f) Secondary mineralization effects; in particular, the factors controlling their development, their impact on metal leaching over time, and their dissolution where required;

(g) Metal tolerance and galvanic effects; in particular, ways by which the galvanic effect between pyrite and chalcopyrite can be used advantageously in leaching systems;

(h) Scaling laws and guidelines to investigate size controlling effects;

(i) The development of a data base and computer modelling;

(j) Improved system design, primarily to enhance oxygen supply and solution and air dispersion within the leach regime;

(k) Cheaper, more efficient and locally supplied construction materials;

(l) Finally, and totally ignored in the literature, the identification, interpretation and resolution of problems occurring in industrial leaching operations, and the capabilities required to optimize the ongoing process.

## 1.5 The technological capabilities required for bacterial leaching technology development

Having outlined the factors controlling the bacterial leaching mechanism and the ways in which the process may be optimized; and since the potential for the application of bacterial leaching in developing countries was considered positive, as a conclusion to this chapter, a scheme is developed which sets out the basic requirements for technology development in this area. The scheme takes account of the factors controlling the bacterial leaching mechanisms and the ways in which the process may be optimized.

This scheme consists of the categories of technological capabilities which are required to design and implement a process of endogenous technical change in the area of bacterial leaching. The term endogenous technical change is employed here to mean technical change designed, implemented and controlled from within the countries concerned - which is not to imply that foreign technology-related inputs (including experts) do not play an important role.

The scheme presented focuses primarily on bacterial leaching heap systems, that is, a system which can be optimized since it is developed purposefully for leaching. While the scheme is obviously applicable to dump leaching systems it would require more detail on reactor design and initial flotation processes if it were to be extended to include concentrate leaching. Similarly the scheme could be extended to include recuperation processes - particularly solvent extraction and electrowinning and also techniques for the recovery of precious metals, for example, silver or gold from effluent solutions.

No cost data is given for two reasons. Firstly, the difficulty of obtaining standardized prices for equipment and laboratory instruments; secondly, each mine and mineral development project will have its own cost structure (see section 1.2.2). For example, the cost of drilling, sampling, mining, transporting and dumping will all be directly related to the geological and mineralogical characteristics of each mine site, as well as the size of the mine and the nature of the company's overall operational activities. Therefore the "funds" component of the capability framework should be considered a guide to the fundamental elements of its cost structure to be determined individually for each particular project rather than the actual costs that could be expected to occur in bacterial leaching technology development.

1.5.1 Methodological note

The concept of technological capability, as it is often referred to in the technology policy literacure, has little practical application unless it is specified as a capability to effect a particular type of activity and a component of a process which needs direction and co-ordination before it can effect technicai change. In relation to technical change in the area of bacterial leaching, the capabilities required to develop, implement and control a technically and economically efficient bacterial leaching process project can be categorized into four major sets of technical change activities. These are: (i) process route selection and the decision to include bacterial leaching in a mineral project; (ii) evaluation of the leachability of the material and the design of parameters for scale-up; (iii) pilot-plant testing; (iv) designing, installing, controlling and optimizing a technically and economically efficient bacterial leaching project at the industrial scale.* For each set of activities it is possible to define various tasks, requirements of personnel (who will embody interrelated elements of knowledge, skill and experience), and requirements of techniques, facilities, equipment and funds. Finally, an overall context is outlined within which the technical change activities take place, setting out the requirements for the direction, organization and co-ordination of the process.

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* This scheme is based on the literature survey and general field-work research presented in the preceding sections. However, the contribution of some of the technical information in documents from the Andean Pact Copper Project should also be acknowledged. This source material is listed in full in annex IV of the present paper.

1.5.2. A technological capabilities scheme for bacterial leaching technology development

A. ACTIVITY: Choice - process route selection and the decision to include bacterial leaching in a mineral project

TASKS

Estimating tonnage, grade and characteristics of the mineral deposit, particularly of the material that can be leached and precious metals which can be recovered.

Study of the market for end-products e.g. cement copper, copper sulphate crystals, electrowon cathodes.

Collection of information on possible process routes and related technology development, particularly with respect to bacterial leaching, e.g. state of research in the world, centres of expertise, industrial applications etc.

Initial technology and process route assessment including evaluation of possibility of applying bacterial leaching technology to dumps, heaps, tailings, in situ reserves or concentrates and consideration of recuperation processes.

Informed decision to go ahead with detailed evaluation of leaching characteristics of the rocks, preliminary engineering design of process routes and allocation of personnel and funds to the bacterial leaching project.

Assessment of social impact of the project and making and carrying out related recommendations, particularly with respect to women workers on waste dumps and private small-scale miners who rely on mine water supplies.

PERSONNEL: Knowledge:

General - of current trends in world mineral industry, technology development, particularly bacterial leaching (e.g. current state of the art, centres of expertise, industrial applications, market prospects etc.)

Specific - of ore deposits e.g. detailed mineralogy and host rock characteristics; mineral concentration and tonnage, geology of region and mine and plant site, including hydrogeological characteristics (mine water, fresh water, permeability of base rock and nature of water table) of where mineral-rich waste has been dumped; of organization of labour at mine site and existing patterns of resource (e.g. dumps, mine water) use, of implications of all these factors for applying bacterial leaching at the chosen mine site.

**Skill inputs:** Combined - geologist, mineralogist, hydrogeologist, metallurgist, miner, mining engineer, chemical engineer, bacterial leaching expert (an international expert could be contracted at this stage), management and technical support - at this stage, until the requisite skills have been built up locally.

**Experience:** In evaluation procedures for hard rock, tailings and dumps, in interpreting geological evaluations; in both production and decision making for process route selection; in industrial operations of bacterial leaching; in working as a team.

**TECHNIQUES:** Geological evaluation: Dynamiting; drilling; representative sampling.

Ore analysis and assaying.

Mineral characterization.

Data interpretation.

Literature search.

Technology search.

Market study.

**FACILITIES:** Access to mine site.

Laboratory: mobile is preferable and as close to mine site as possible.

Information storage and retrieval systems including well-stocked and organized library. a/

Contacts and efficient communication systems with foreign experts, institutions and firms and other divisions within the firm.

**EQUIPMENT b/ AND FUNDS**

| | | | |
|---|---|---|---|
| Mine Site: | Items: | Drills | Estimated US$ |
| | | Churn drill | |
| | | Cyclone drill | |
| | | Air plane drill | |
| | | Wooden shaft blocks | |
| | Activity: | Drilling per metre in: | |
| | | Hard rock | |
| | | Soft rock | |
| | | Dumps | |

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a/ Relevant books and journals could be listed.

b/ Costs will ultimately depend on the geological characteristics of the mine site as well as the particular technique, equipment and instruments chosen.

Laboratory: Items: Crusher
Pulverizer
Titrator
Balances
Atomic spectrometer
Mineralogical microscope
Glassware
Accessories

Activity: Chemical analysis
Mineralogical analysis

General: Items: Library and information (relating only to bacterial leaching)
Book budget for year
Journal subscriptions for year

Labour: Salaries of production and laboratory staff
Short-term contract of bacterial leaching expert

CONTEXT: A multidisciplinary team working together in close and continuous co-operation with both production personnel, research staff and management. The co-ordinator of the team should be a person open to new ideas and have the ability to:

- Obtain the support of management for these ideas;
- Obtain and maintain support of working team and co-ordinate the activities of bacterial leaching experts, metallurgists and mining engineers;
- Choose foreign experts and know at what stage to contact them and what information can be obtained;
- Persuade the foreign engineering team carrying out the prefeasibility study for the mineral project both to consider the possibility of bacterial leaching and accept the participation of the local team in the project.

B. ACTIVITY: Evaluation of the leachability of the ore and the design of parameters for scale-up

TASKS: a/ Mine water: Location of origin and drainage patterns of mine water;
Collection and analysis: Selective sampling at various sites;

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a/ Detailed procedures for these tasks can be set out in the scheme.

Chemical analysis for major elements (e.g. copper, ferric iron etc.) and pH testing;

Analysis of biological characteristics and identification of leaching bacteria;

Decision to proceed to evaluation of leachability of ore.

Bacterial cultivation and strain selection (ongoing research into the desirable and undesirable characteristics of the bacteria and leaching behaviour of the ore and possibilities of genetic manipulation). a/

| | |
|---|---|
| Shake flask tests: (duration of days or weeks): | Grind analysed samples (e.g. 10-30 gr. of 400 mesh);<br>Add nutrient solution with bacteria (about 75 ml.);<br>Adjust pH to 2 and temperature to 30-35°C;<br>Agitate furiously;<br>Frequent (at least daily) checking, registering of data and control (e.g. pH, $Fe^{3+}$ and copper solution)<br>Check sample for residual mineral values;<br>Plot metal extraction as function of time; |

Decision to proceed to column testing stage.

| | |
|---|---|
| Column tests: (duration 6 months to 3 years): | Mineralogical analysis of ore to be leached; determination of copper content;<br>Set up columns of different heights and diameters and fill with ore of different particle size;<br>Set up solution application, circulation, collection and recuperation system and oxygen supply;<br>Prepare solution, begin irrigation and inoculate bacteria;<br>Assess determinant variables e.g. initial and continuing acid consumption, oxygen availability, particle size, precipations and fines formation, effect of particle size, bacterial yield and activity etc;<br>Determine copper extraction as a function of time and pregnant solution grade as a function of extraction. |

Economic evaluation of the potential demonstrated during column testing.

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a/ In parentheses since this is a task which is optional and may be carried out separately from the activity as a whole.

Decision to proceed to pilot plant stage.

Interpretation of data and continued experimentation to determine parameters for scale up.

PERSONNEL: Knowledge: General - of how to plan and carry out a R and D programme; of how to extract parameters for scale up; of the literature and current R and D being carried out in bacterial leaching.

Skill inputs: Mineralogist, chemist, hydrometallurgist, microbiologist, especially contracted bacterial leaching expert (either local or international, until the requisite skills have been built up locally), design engineer, technicians, management,

Experience: In carrying out bacterial leaching R and D or training in the procedures. In understanding exactly why or why not a particular ore sample leaches and why the bacteria in particular tests are absent or prolific. In working as a team.

TECHNIQUES: Standard techniques for chemical and microbiological experiments:

Shake flask and column test procedures.

Literature search.

FACILITIES: Chemical and microbiological laboratory.

Column room.

See also facilities in section A above.

EQUIPMENT AND FUNDS: Items: Estimated US$

Phase contrast microscope (with magnification strength between x400 - x1000)
Fermenter
Incubator
Biomass analyser
Precision balance
Selected nutrients
Measuring instruments (pH, oxygen, $Cu^{2+}$, $Fe^{3+}$)
Drying oven
Centrifuge apparatus
Electrochemical apparatus
Gyrating shaking cabinet
Glassware and accessories
Columns (e.g. of PVC)
Plastic buckets and turbines
Heater and thermostat
Micropumps and flow systems
Glassware and accessories
Design engineering equipment

**Activities:**

- Mine water collection and analysis per sample
- Electrochemical analysis per sample
- Shake flask test per sample
- Column test per sample
- Bacterial cultivation and maintenance
- Design engineering

**Labour:**

- Salaries of the team members
- Contract of bacterial leaching expert
- Grant(s) for university student(s) to work on thesis

CONTEXT: A multidisciplinary team working and meeting together, jointly interpreting findings and constantly referring back to the production sector (e.g. to the site of mine water and bacterial origin and to the material to which the process will be applied).

An awareness of current R and D in the world (including national research institutes and universities) relating to bacterial leaching and in particular advances in genetic manipulation of leaching bacteria.

University students could perhaps be provided with grants to do thesis work of relevance to the bacterial leaching project.

A well-informed decision making capability within the team organized by its co-ordinator.

C. ACTIVITY: Pilot plant testing

Design and implementation of pilot plant heap and recuperation plant according to the parameters developed (or to the dump already existing) and the design of further parameters for scale up to the industrial plant.

TASKS: Consideration of parameters developed and informed planning of pilot plant project (e.g. organization of tasks and personnel).

Choice and location of plant site.

Detailed design and process engineering of pilot plant and preparation of infrastructure.

Selection of equipment and negotiation of technology transfer.

Preparation of ground.

Mining of ore (and preliminary crushing if necessary).

Transportation of ore.

Distribution of ore and heap(s) construction.

Installation of equipment and preparation of leach solution.

Start up - solution application.

Inoculation of bacteria.

Standard control checks (pH, grade and composition of pregnant solution, bacterial yield etc.) and adjustments.

Tests to optimize: leach system design, solution management (including rest cycles) and bacterial activity and yield.

Determination of extent and rate of extraction and average grade of pregnant solution as a function of extraction.

Economic evaluation and feasibility study of the process and extrapolation to provide provisional data for an industrial-scale operation.

Decision to proceed to industrial plant stage.

Interpretation of data and continued experimentation to determine parameters for scale up.

Ongoing R and D laboratory relating to optimizing bacterial activity and investigating leaching characteristics of the ore.

PERSONNEL: Knowledge: General - of pilot plant design and development; of factors affecting scale up in leaching systems; of the possibilities of and constraints upon optimization.

Specific - combined knowledge of laboratory results, rock characteristics and site-specific factors affecting the optimization routes for the particular leach system planned. These factors include: content of soluble copper; rate of acid consumption; the characteristics and requirements of the microbiological population; oxygen requirement and availability, pH of leach solution; methods of solution application; optimum leaching rates; ferrous-ferric ratios; effect of pyrite; maximum height and tonnage; compaction and segregation; effect of rest periods.

Skill inputs: Hydrogeologist/geographer, soil engineer, geologist, microbiologist, chemical engineer, metallurgical engineer specializing in hydrometallurgy, miner, mining engineer, economist/management.

Experience: In bacterial leaching pilot plant design and testing or training in the procedures; in industrial-scale operations (preferably hydrometallurgical); in working as a team.

TECHNIQUES: Heap, dump or reactor leaching system; recirculating (by pump) or continuous (by gravity) solution flow system; spray or submerged irrigation system; scrap iron cementation or solvent extraction electrowinning recuperation systems.

FACILITIES: Mobile laboratory facilities at the pilot plant site.

See also facilities for sections A and B above.

EQUIPMENT AND FUNDS:

Items: | Estimated US$
--- | ---

- Design engineering materials
- Mobile laboratory with standard testing and control instruments (see sections A and B above)
- Ground preparation per $m^2$
- Plastic pumps (resistant to Ph7 and 5 grams per litre $CuSO_4$), motors protected against humidity (1,500 rpm if needed to work at altitude), accessories, spare parts
- Plastic piping and irrigation system
- Collection tanks with impermeable lining
- Sulphuric acid
- Biological nutrients
- Cementation pilot plant, equipment and inputs
- Solvent extraction-electrowinning pilot plant, equipment and inputs

Activities:

- Design engineering
- Mining per cubic ton
- Crushing per cubic ton
- Transporting per cubic ton
- Heap construction per cubic ton
- Operating costs:
  - Ongoing inputs bacterial leaching plant (energy for pumping)
  - Ongoing inputs cementation plant

Ongoing inputs SX-EW plant

Ongoing testing

Repairs and maintenance

Labour costs

Costs of contracting bacterial leaching or solvent extraction expert

CONTEXT: Pilot plant should be located at the mine site as close to the planned industrial site as possible due to the environmentally sensitive optimal conditions for the local bacteria activity.

The programme requires at least two full-time skilled personnel: one for applied R and D testing, interpreteting data and making ongoing improvements. The other for administration, co-ordination and direction of the ongoing operation.

Need to ensure participation of and flow of information between mining engineers and metallurgists (the former group should be included in any related training programme).

Active participation of team in design of parameters for industrial plant (e.g. fortnightly discussion meetings).

D. ACTIVITY: Designing, installing, operating and optimizing a techrically and economically efficient bacterial leaching project at the industrial scale

TASKS: Study of pilot plant programme especially problems encountered and parameters developed

Choice and location of plant site

Detailed design and process engineering of industrial plant and infrastructure

Planning and organization of the project

Selection of equipment and negotiation of technology transfer

Preparation of ground (if necessary)

Mining of ore (and preliminary crushing if necessary)

Transportation of ore

Distribution of ore and heap(s) construction

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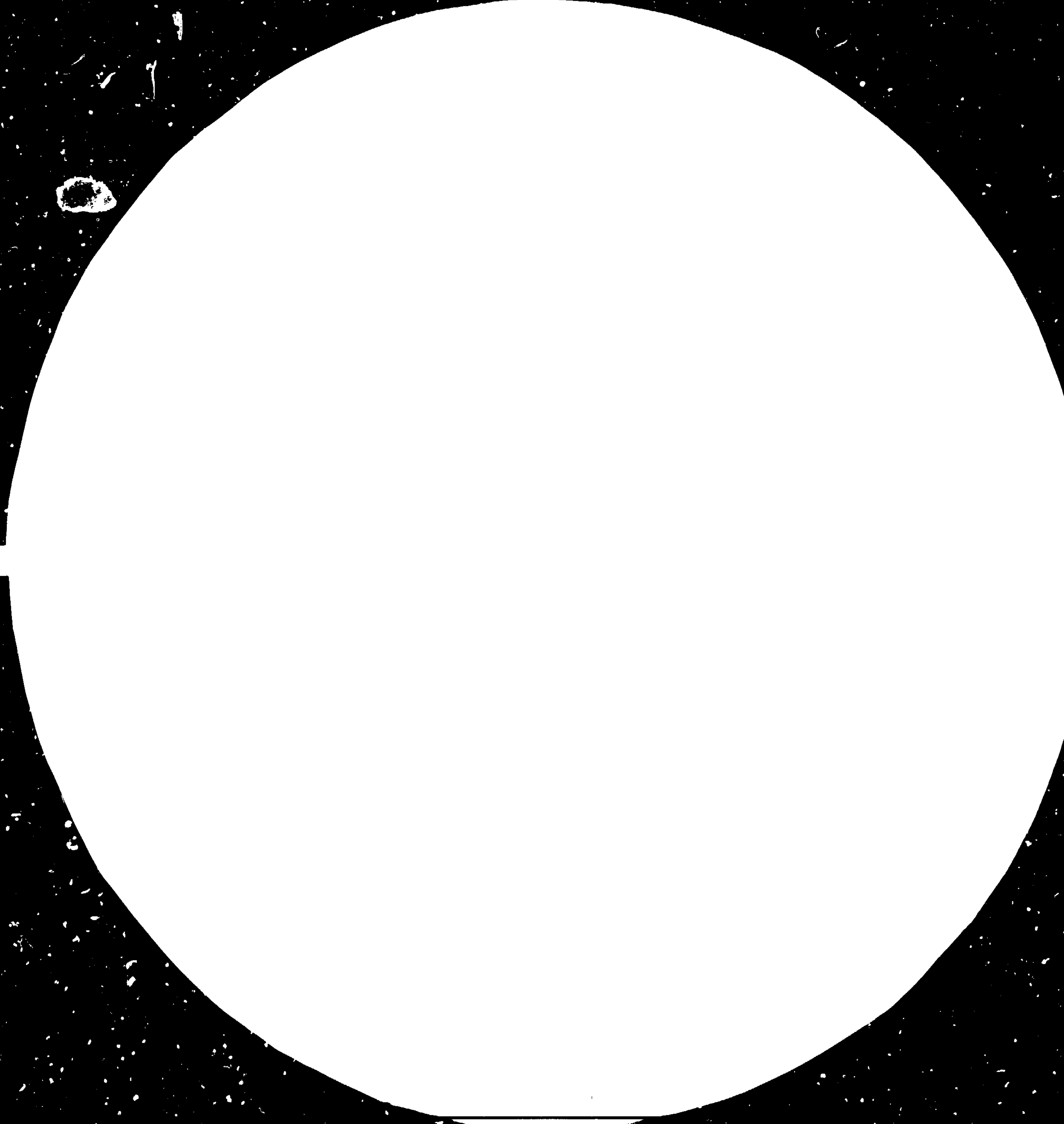

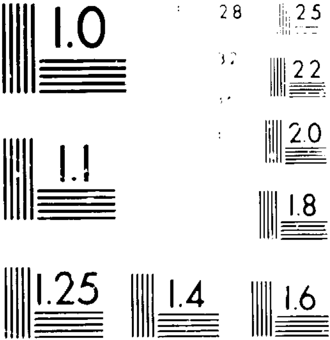

1.0
28
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

Reliable sampling and ore assaying to determine content, grade and characteristics of soluble copper in each heap

Installation of equipment and preparation of leach solutions

Start up - solution application

Inoculation of bacteria

Standard control checks and adjustments

Optimization of leach system design, bacterial activity and yield and solution management

Ongoing related R and D (e.g. genetic manipulation possibilities)

Determination of extent and rate of extraction and average grade of pregnant solution as a function of extraction

Ongoing economic and technical evaluation of the industrial operation checked against results of pilot plant programme. Related decision to contract a bacterial leaching expert to advise on particular problems

Decision to set up another industrial operation using parameters extracted from the ongoing one

Decision to continue with the industrial operation

Decision to terminate operation when pregnant solution grade falls below what is considered economically viable.

<u>PERSONNEL:</u> <u>Knowledge:</u> General - of factors affecting scale up to industrial plant; of other industrial bacterial leaching operations in the world; of equipment suppliers and how to negotiate with them; of market prospects for end-products.

Specific - combined knowledge of R and D results, pilot plant programme, rock characteristics and site-specific factors affecting the optimization of the industrial operation; ability to know whether a fall in grade of pregnant solution indicates the extraction of all soluble copper or a problem which may be resolved. See also section C above.

<u>Skill inputs:</u> Hydrogeologist/geographer, bacterial leaching expert, microbiologist, chemist, miners, site workers and technicians, mining, metallurgical and chemical engineers, economist/management.

**Experience:** Industrial experience particularly relating to leaching operations; training at an industrial-scale bacterial leaching plant; in working as a team.

**TECHNIQUES:** The same as for section C above but at the industrial scale.

**FACILITIES:** Access to mining, transportation and dumping equipment; basic plant infrastructure and ground communications with mine site and mobile and central laboratory.

**EQUIPMENT AND FUNDS:**

**Items:** | Estimated US$
---|---
Design engineering materials |
Mobile laboratory and instruments |
Ground preparation per $m^2$ |
Plastic pumps, motors (numbered depending upon plant dimensions and recirculation requirements) accessories and spare parts |
Plastic piping and irrigation system |
Collection tanks with impermeable lining |
Sulphuric acid |
Biological nutrients |
Cementation plant, equipment and inputs |
Solvent extraction-electrowinning plant, equipment and inputs |

**Activities:**

Detailed design and process engineering
Mining per cubic ton
Crushing per cubic ton
Transporting per cubic ton
Heap construction per cubic ton
Operating costs:

Ongoing inputs bacterial leaching plant (energy for pumping)

Ongoing inputs cementation plant

Ongoing inputs SX-EW plant

Repair and maintenance

Labour costs

Costs of contracting

Bacterial leaching or solvent extraction

Experts for assistance or on-site training

Financing visits to other industrial plants or conferences

CONTEXT: Industrial plant needs to be located as close to the mine site and pilot plant as is geographically/hydrogeologically feasible.

Multidisciplinary team should include personnel who have worked in each stage of the technology development process.

The team needs to be in close contact with research and production personnel and constantly referring back to library and information collection facilities, ongoing R and D (within the firm, in other national and international institutions and firms) and trends in costs of inputs and prices for end-products.

Mechanisms should be developed so that ideas to improve production are recognized, evaluated and tested. This implies the project co-ordinator should be in close contact with all operating personnel.

Natural changes like decline in copper content, particle size decrepitation, precipitations, dilution of pH in rainy seasons, fall in grade of pregnant solution etc. should be anticipated and the necessary adjustments made.

The co-ordinator should ensure the smooth running of all aspects of the operation, including relations within the team and between the team and mine personnel, metallurgists and management.

Mechanisms should be created which facilitate the diffusion of the technology to other mine sites.

# CHAPTER II

# THE APPLICATION OF BIOTECHNOLOGY TO THE MINERALS INDUSTRY: THE CASE OF THE ANDEAN PACT COPPER PROJECT AND SOME IMPLICATIONS FOR POLICY FOR DEVELOPING COUNTRIES

## 2.1 Summary

### 2.1.1 The changing technological context of mineral development

In the present context of low and unstable metal prices, the minerals industry cannot ignore economic and environmental considerations such as the depletion of reserves, the decline of ore grades, stricter pollution regulations and rising investment and energy costs.

As easily accessible high-grade mineral concentrations are depleted, many mineral deposits scheduled for development are low grade and disseminated sulphide porphyry bodies. In the past these were mined mainly for one mineral, generally copper. Now it is becoming increasingly necessary to recover associated by-products which, depending on regional zoning, may be molybdenum and gold or lead, zinc and silver, and to extract pollutant elements. Mine capacity has to be stretched further to compensate for declining ore grades by recuperating resources previously not exploited - like dumps or marginal overburden. This is leading to a closer relationship between the mineralogy of ore deposits and the techniques that can be used for the extraction and recovery of associated metals.

Corresponding technical developments in the minerals industry over the last decade reveal a number of technically viable choices of process.

Recent innovations in pyrometallurgy aim at reducing energy costs and recovering pollutant sulphuric gases. These include: matte-making processes, such as flash furnaces; oxygen-sprinkling smelters and electric furnace smelting; and continuous matte-making and converting techniques like the Noranda and Mitsubishi processes.

Similarly in hydrometallurgy, new processes have been developed for leaching sulphide minerals and mixed ores using chloride, cyanide, ammoniacal and bacterially-activated solutions. These tend to require less purchased energy, and reduce investment costs and pollutant effects. Solvent extraction and electrowinning technology emerges as an economic alternative to conventional smelting and refining for recovering metals from these solutions.

It is not realistic to conclude that any one production process, or pyrometallurgy or hydrometallurgy, will dominate because it costs least. An essential feature of the minerals industry is that the geological characteristics and geographical location of each mine site mean that each requires a specially designed process, rather than one conforming to more general parameters.

In the present international climate, both planners of new industrial projects and operators of existing mines must consider a wider and more complex range of processes to find the optimum one exhibiting the best over-all economics.

Within this changing technological context of the minerals industry, and in the light of foreseeable advances in biotechnology, the present paper maintains that the bacterial leaching of minerals is an ideal process for developing countries to exploit their mineral wealth.

Bacterial leaching is a naturally occurring process whereby certain microorganisms, notably Thiobacillus ferrooxidans (T. ferrooxidans), facilitate the conversion of normally insoluble sulphide minerals, such as pyrite, chalcopyrite etc., into water-soluble forms, thus freeing the associated metal ions for subsequent recovery. The bacteria obtain the energy they need for functioning and growth from the oxidation of inorganic compounds of iron and sulphur and so accelerate the oxidation process of ferrous ions to ferric sulphate and sulphuric acid solutions up to $10^6$ (one million) times faster than would normally occur in the presence of air alone. This in turn significantly speeds up the dissolution of water-soluble sulphide minerals. In addition, there is reliable evidence to suggest that several bacteria strains (see section 1.3.1.3) directly attack the oxidizable parts of normally water-insolubie sulphide minerals, transforming and breaking them up into water-soluble forms.

Since bacteria are living organisms, they require special conditions for maximum functioning and growth and thus optimum oxidation and leaching rates. In general they require abundant oxygen, a acidic pH, specific nutrients and a moderate temperature while some dissolved metals, for instance uranium, can be toxic to certain strains. However, there are precise conditions which enable optimum bacterial activity and these are generally best fulfilled for each bacteria strain by its indigenous environment.

Similarly, the characteristics of the leach system - its mineralogy, particle size, dump porosity, air updraught, temperature profile etc. - will also affect the efficiency of the biological reactions and thus the amount of, and rate at which the contained metal can be taken into solutions.

It is these wide-ranging and complex requirements and conditions which provide the scope for developing parameters to optimize the bacterial leaching process for economic gain.

Three main ways in which bacterial leaching could broaden the range of possible process routes for mineral extraction and metal recovery were presented in chapter I. They are:

(1) The leaching of sulphide values from dumps of waste from previous mining operations which worked with a higher cut-off grade; or the "flushing out" of old mines using in situ leaching techniques, thus recuperating "extra" mineral content and, in so doing, preventing natural pollution by uncontrolled metal-rich effluents in drainage water.

(2) The leaching of overburden from newly-developed mineral deposits, and of marginal ore during ongoing operations, in heaps specifically designed to optimize the leaching process to obtain remuneration in the short term and compensate for undercapacity.

(3) The more novel possibility of leaching sulphide concentrates in vat or confined systems under highly controlled conditions.

It was maintained that these developments have important implications for mineral-producing developing countries, not least with respect to technical choice and decision making, since the majority of sulphide porphyry deposits are located within their boundaries.

Three corresponding sets of reasons were discussed to explain why bacterial leaching alternatives offered much potential to developing countries in particular.

(1) Most of the developing countries have long mining histories. So in mines where cut-off grades have been lowered over time, or which were mined for only one mineral, there probably will exist dumps of currently economically viable ore. Similarly, many abandoned underground mines exist from which the remaining mineral values may be leached. Older dumps and mines, because of the unrefined ore assaying techniques and inefficient plant and equipment of the time, may contain up to 2 per cent copper. In the light of depressed markets and high investment costs there is increasing pressure on mining companies to stretch installed capacity rather than open new mines. A dump or in situ bacterial leaching operation could be carried out at relatively low marginal cost. For example, investment costs may be between US$ 2-5 m, depending on the mine's geological and geographical characteristics and the recovery techniques chosen. The chemical and biological reactions are self-sufficient and little purchased energy would be required for pumps and solids handling. The recovered copper could be sent to the smelter, which at this stage in the mine's life would probably be running at undercapacity, or if the ore's tonnage and leachability warrant it, solvent extraction could be undertaken.

Examples of such operations are found at Cerro de Pasco in Peru; in Chile, CODELCO has plans to introduce in situ leaching at El Teniente and MINERO-PERU plans to employ bacterial leaching to extract remaining sulphide values from its exhausted oxide heaps

(2) Many developing coutries, including Argentina, Brazil, Bolivia, Chile, Colombia, Ecuador, Indonesia, Panama, Papua New Guinea, the Philippines and Peru, are now embarking upon process route selection for new mineral projects. Since most of their mineral deposits are copper sulphide porphyry bodies, bacterial leaching technology could be considered in many of them.

Such mineral deposits usually require open pit mining and thus the removal of large tonnages of overburden. This overburden, which often contains economic quantities of copper sulphides due to the disseminated nature of the ore deposits and its gradual boundaries, could be separated into waste proper and leachable ore. At relatively little additional cost to the mining operation as a whole, heaps could be constructed according to the optimal conditions for the leaching of that ore. The investment cost would vary, depending on the extent to which technical changes are required and considered worthwhile, but would be relatively low - say up to US$ 50 m in relation to a mining project's total investment costs of upwards of US$ 1 billion. The profits subsequently obtained (after a leach cycle of two to three years) could be used to offset the costs of developing the mine itself and help to reduce the burden of loan repayments. In the same way revenue from dump leaching a previous mine's waste may contribute towards the cost of a new mine. Heap leaching operations of this type are being developed by CENTROMIN at Toromocho, Peru, and by CODELCO at Chuquicamata, Chile.

(3) In view of the current problems facing energy-intensive and pollutant pyrometallurgy and the growth of new options in hydrometallurgy, it is expected that vat or confined bacterial leaching systems may become an economic alternative to smelting for obtaining copper concentrates in the future. Recent pilot plant research indicates that in the light of current energy costs, the bacterial leaching of copper concentrates may be carried out successfully at 60-70 per cent of the cost of a similar smelting operation, and associated precious metals like gold and silver economically recovered.

The majority of new projects and unexplored mineralized zones are in the developing countries and exploration endeavours and mine development take decades. Therefore, the possibility is very high that concentrates leaching may form a primary process route alternative for these new projects; especially given foreseeable advances in biotechnology and genetic engineering, the higher degree of control that can be exercised over confined leaching systems and the improvements being made to complementary solvent extraction recovery techniques.

It also was noted in the previous chapter, that bacterial leaching technology can be adapted to solve a range of metallurgical problems. These include the separation of lead from zinc concentrates; of arsenopyrite from copper smelter feeds and of pyrite from disseminated gold-bearing ore, thus freeing the gold. Again, given the changing technological context in which new mineral deposits will be developed, and the increasing complexity of process routes for individual mines as by-products and impurities require recovery, the development of these processes may be particularly relevant for developing countries. For example, COMIBOL's operations in the Quechisla region of Bolivia, have to overcome problems of copper contaminated lead and zinc concentrates; CENTROMIN's copper smelter at La Oroya, Peru, has to tackle problems of arsenic pollution, and gold occurs in association with pyrite in many regions of Peru, Bolivia, Colombia and Ecuador.

Despite the potential offered by bacterial leaching it is important to note that virtually all the examples of the commercial applications of this technology are to ancient dumps of what was previously considered waste. Most of these are located in the industrialized countries (e.g. Canada, the Soviet Union and the south-western United States). The significance of this is that these dumps are not operating according to parameters to optimize the leaching process since the microbiological component of sulphide leaching was not realized at the time of their construction. So, although these bacterial leaching operations account for over 10 per cent of the production of United States copper, they generally have recuperation rates of between 5 per cent and 40 per cent of the contained metal in periods of five years or more.

Some characteristics of the major commercial bacterial leaching operations are summarized in annex I, and typical investment costs are noted in table 3. These operations are generally low-cost investment projects embarked upon to recover extra copper values, or to reduce pollution, from naturally emerging metal-bearing acidic effluents from dumps.

It is the complex requirements of the leaching bacteria which explain the suboptimal recuperation rates from present dump leaching operations. For example, waste is often placed in large mounds in valleys for dumping convenience. As a result dump interiors may be starved of air and temperatures in the core may rise due to the oxidation of the pyrite and insufficient oxygen updraught for cooling. This makes the environment inhospitable for bacteria and thus reduces the leaching of the contained mineral content. Similarly, if due to weathering or dump volume the ore decrepitates easily, fines will be formed which constrain leaching reactions. The consequent rise in pH reduces bacterial activity both directly and also indirectly through causing iron salts to precipitate, coating mineral particles and leaving them inaccessible to bacterial and acid attack.

Three main routes of optimization are identified and discussed in the present paper. These are: leach system design, solution management and improvements of the bacteria. Research and pilot plant experiments indicate that recuperation rates of over 80 per cent can be achieved in time periods of between eighteen months and two years if such optimization routes are followed.

In a dump leaching system optimization is restricted to solution management, with some possibilities of bacterial activity improvements. For example, solutions can be distributed to the dump surface through spray systems to enhance oxygen penetration; solution application rates and rest periods can be devised; and $Fe^{3+}$ and pH contents can be systematically controlled. An ubiquitous indigenous bacterial population will probably out-compete any improved strain later inoculated into the dump. However, as an outcome of microbiological research, in the future it may be possible to inoculate barren dump interiors with high temperatures or mixed leaching species.

There is obviously more potential for optimizing heap or confined systems since they are constructed purposely for leaching. Optimal height, shape, tonnage and particle size can be determined; correspondingly a "finger heap" system may be constructed which maximizes oxygen uptake and cooling and prevents percolation problems through fines formation; optimal locations can be selected and ground surfaces prepared, if necessary, to prevent solution losses. In addition to optimization procedures through planned solution management, improvements to the bacterial population can be made through inoculation of selected and adapted strains, the creation of mutually beneficial mixed cultures, and the addition of growth-stimulating nutrients and elements. Genetic engineering may offer ultimately the greatest potential for improving leaching bacteria. For example, cell adjustments could be made so that the bacteria selectively leach particular sulphide minerals or are unaffected by certain toxic substances; and the enzymic reactions controlling oxidation could themselves be speeded up.

However, it cannot be overemphasized that the cost structure of optimizing a bacterial leaching project is highly dependent upon the geology and geography of the mine location. The rock type and its natural particle size after dynamiting will determine the necessity for preliminary crushing, the addition of extra acid or the special design of finger dumps; the soil types and hydrogeology of the location of the leaching operation will determine the need for prior ground surface preparation and the nature of the solution collection system; and the availability and characteristics of local acidic mine water and vibrant indigenous bacteria will ultimately determine the efficiency of bacterial leaching for a given mine site. The characteristics of the principal routes to optimization are, therefore, highly site specific.

The principal implication of all this is that there exists no precedent in the industrialized countries of optimized bacterial leaching operations. There are no general models upon which the developing countries can design their leaching projects and, as a source of technology transfer, the potential of the industrialized countries, although important, is limited.

In addition, linking biotechnology with the mining industry demands a combination of a wide range of knowledge, skill and technical inputs which in their diversity distinguish bacterial leaching projects from other technical projects in the minerals industry.

In this context, based on a detailed literature survey, discussions with experts and field-work at the mine site, a scheme was constructed which sets out the categories of technological capabilities required for the development of an "abstract" economically and technically efficient bacterial leaching project where the objective is to design and implement a process of endogenous technical change. Endogenous technical change means technical change designed, implemented and controlled from within the countries concerned, which is not to imply that foreign technology-related inputs cannot play an important role.

These technological capabilities are considered in the context of four major sets of technical change activities. These are: first, process route selection and the decision to include bacterial leaching in a mineral project; secondly, evaluation of the leachability of the material and the design of parameters for scale-up; thirdly, pilot-plant testing; and fourthly, designing, installing, controlling and optimizing an efficient bacterial leaching project at the industrial scale.

For each category of technical change activities the scheme specifies tasks, requirements of personnel (which will embody interrelated elements of knowledge, skill and experience) techniques, facilities, equipment and funds and a context in which the technical change activities take place.

The technological capabilities scheme forms the basis for the critical analysis of the Andean Pact Copper Project and the guidelines which follow, in section 2.2, for bacterial leaching technology development at the project level.

### 2.1.2 The Andean Pact Copper Project

The Andean Pact Copper Project represents one of the few examples of the development and application of bacterial leaching technology within the developing countries. In addition to its intrinsic relevance as a technology development project in the area of biotechnology and the minerals industry it is also interesting since it was designed to engender a process of endogenous technical change in the participating countries.

Consequently, a specific strategy of technological capability development was designed to achieve this. Essentially it involved the utilization and development of local resources and skills in the area of bacterial leaching assisted by the international transfer of technology-related inputs both from developed countries and between developing countries and co-ordinated by the Technology Policy Group of the Andean Pact. The resulting projects were aimed at copying, adapting and creating technology through joint efforts. The idea was that they should achieve specific social and economic objectives and in doing so act as instruments of integration. Four projects have been embarked upon. These are: the Copper Project, the Tropical Woods Project, the Food Project and the Rural Project. *

This set of projects was discussed within the Andean Pact in the context of the failure of other policy projects and the complete disillusionment of decision makers and firms with the capacity of R and D institutes to create technology within the countries of the Andean Group. Three factors were thus to be crucial in their choice of future projects: (i) the assurance of their economic and technical success; (ii) their potential impact; and (iii) their political feasibility.

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* The Andean Project in Tropical Woods was approved by Decision 89 of the Board of the Cartagena Agreement in 1975. Its objectives were to integrate the forestry reserves of the Andean countries through joint activities in technical, industrial, economic, legal and policy areas. These activities have included the setting up of 11 subregional laboratories and the participation of 200 technicians; the development of a classification system of structural woods and a design manual for construction; and, the development of low-cost housing "pilot villages".

The Andean Project for Technology and Development in Area of Food and Nutrition was approved by Decision 126 of the Board of the Cartagena Agreement in 1979. Its objectives were to produce locally foods of high protein and calorific value at relatively low cost destined for the vulnerable groups of low income sectors of the population of the subregion and to substitute for some importation of these foodstuffs. It has several activities in progress; these include projects within the milk, flour and fish industries.

The Andean Project for Rural Technology Development was approved by Decision 167 of the Board of the Cartagena Agreement in 1981. Its principal aim is to generate, transfer and diffuse technological solutions to the Andean (sierra) zone of the subregion in order to improve the management of natural resources and agriculture by the small farmer. Five microregions in each member country have been chosen and local farmers will be participating in the development of sub-projects in each microregion.

The general goals of these projects are:

(a) The solution of a mutual technical problem in a co-operative way through the integration of the participating countries so that teams would be working complementarily and not parallel;

(b) The formation of teams with a problem-solving capacity in all activities from R and D to industrial production;

(c) The introduction of these teams as viable alternatives to foreign consultants at the industrial level;

(d) The creation of an infrastructure which would form a base to enable the technology thus generated to be adapted to other areas of industry.

It was decreed that when these projects were formulated they must include a detailed definition of the problems, objectives, methodology, evaluation criteria, human and material requirements, time scale and possible economic and social benefits. It was planned that these same factors should form the basis for the control and evaluation of each project.

The Andean Pact Copper Project was a collaborative project involving only Bolivia and Peru and was designed to solve the mutual problem of the recuperation of low grade copper from marginal and waste dumps. 90/ The project was originally designed to achieve the following two specific objectives. 91/

(a) To form teams of people capable of efficiently managing the hydrometallurgical technology of copper from the laboratory level up to the design, construction and operation of industrial plants. (These people ultimately should be capable of continuing R and D work and of perfecting, adapting or designing new technologies based on the knowledge transferred through the project); *

(b) To create in Bolivia, Chile and Peru laboratory facilities for analysing, evaluating and developing studies of copper mineral leaching.

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* Unofficial translation from the original Spanish text. The latter part of objective (1) is in parenthesis since it was later omitted from the relevant policy document.

An 18-month planning period (1974-1975), funded by untied assistance given to the Andean Pact's Technology Policy Group, proved to be crucial to the success of the project. * The Pact's Project Co-ordinator was able to use these funds to visit the technology suppliers' bases in Canada and the Federal Republic of Germany and industrial bacterial leaching operations in the United States. It also enabled a preliminary, albeit superficial, survey to be made of both the technical possibilities of applying bacterial leaching in the subregion and the political willingness and existing technological capabilities of the firms and institutions which could participate. Moreover, the Co-ordinator was able to visit the aid donors' central offices in the Federal Republic of Germany to negotiate the aid agreement. This was significant since Chile, the foremost Latin American copper producer, had left the Andean Pact in 1974 and this had weakened the credibility of the project in the distant eyes of the German Agency for Technical Co-operation (GTZ). Indeed it was only through prolonged person-to-person negotiation that agreement was reached and certain restrictive clauses removed from the final contract.

The decision-making processes, explicit and implicit, within the Andean Pact Copper Project are particularly interesting since they involved a whole spectrum of personnel; each with their own perspectives, objectives, capacity and power. They ranged from developed-country-based "assistance" agency officials and technology suppliers to developing-country-based Andean Pact functionaries, government decision makers, company managers, engineers and miners.

Given inevitable political pressures to allot decision-taking roles to particular people and institutes, and the sometimes conflicting necessity to have technically informed personnel in these positions, the decision-making framework had to be carefully designed. Consequently, for each Technology Development Project, the Andean Pact set up what was called a Contracting Committee and it nominated national project managers for each country. The

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* This untied assistance came from the International Development Research Centre in Canada, and the Canadian International Development Agency.

Contracting Committee was to have a formal decision-taking function. The idea was to have on the Contracting Committee an executive secretary from the Andean Pact - in this case the Project's Co-ordinator, who was also the head of the Technology Policy Group - and one high-level government-linked official from each country. The government representative was to have a deputy in case of absence. In practice this was often the project manager who was a technical person in charge of the day-to-day running of the project in each country and reporting to the Contracting Committee on its progress. The project participants were obliged to submit frequent progress reports via the project manager to the Contracting Committee. These were to be reviewed and recommendations made. It was planned that the Contracting Committee should meet every six months. The last meeting of the Contracting Committee was August 1981, however the representatives still have a nominal function since the Copper Project was never officially terminated

Originally the project was planned to begin in late 1974 with the passing of Decisions 86 and 87 by the Board of the Cartagena Agreement. However, due to delays in signing the aid contract and the transfer of finance, it did not begin officially until February 1976.

No alternative to bacterial leaching was considered during project selection since the technology to be developed in this programme was to process previously unexploited marginal ore for which this technique is the only feasible method. However, the technology was not considered in isolation from the copper production process. COMIBOL's principal copper deposit is predominantly oxide so it was decided to develop a separate subproject relating to the sulphuric acid leaching of copper sulphate solutions by precipitation on scrap-iron. This was approved as Decision 86 by the Board of the Cartagena Agreement in 1974. Chile, because of its expertise in this area, was to be the technology supplier. Metal recovery by this method, however, is only one alternative (see section 1.1); so, in the context of its increasing importance in the copper production process, the development of capabilities in the area of solvent extraction and electrowinning was chosen as another complementary subproject. However, it was the bacterial leaching project - approved as Decision 87 by the Board of the Cartagena Agreement in 1974 - which was the core of the Andean Pact Copper Project and which is the main focus of the present analysis.

The programme of technology development included seminar courses, on-site training by foreign experts and visits to dump leaching industrial operations in the United States as well as an international conference in biometallurgy. The project involved the joint participation of CENTROMIN, MINERO-PERU and INCITEMI (now INGEMMET), Peru; COMIBOL and IIMM of Bolivia.

It was concluded that the objectives of the Copper Project have been largely achieved in Peru and to a lesser extent in Bolivia. Furthermore, there has been an impressive diffusion of certain elements of the technology to other mine sites, firms and countries as well as an adaptation of it by the trained teams to help solve other metallurgical problems. Indeed, on the basis of this success, the Andean Pact is planning various follow-up lines of action which aim to consolidate, diffuse and extend biotechnology applications in the minerals sector of the Andean Group, extend the technology development projects to other relevant metals and techniques and to strengthen the Andean countries' negotiating capacity for mining and mineral processing technology. The extent of technology diffusion and adaptation relating to the Andean Pact Copper Project is summarized in table 5 below.

The main achievements of the Copper Project are outlined below.

(1) In the case of CENTROMIN, a large bacterial leaching pilot plant was installed at the Toromocho mine using cementation on scrap iron as the recovery method. The team, based at the Department of Special Projects in the Division of Metallurgy Research at La Oroya, which was created specifically to carry out the Copper Project, provided an important input to the prefeasibility study for the Toromocho industrial project. A new pilot project employing the Krupp solvent extraction-electrowinning plant presented by GTZ to the project is being planned in order to obtain parameters for scale-up. In addition, natural bacterial leaching processes previously at Cerro de Pasco are being optimized, and copper from effluent solution from both the mines and dumps is being recovered electrolytically. These operations also have reduced pollution significantly by the previously freely flowing acidic mine water. R and D is in progress to design a process to recuperate associated silver values.

Table 5

THE EXTENT OF TECHNOLOGY DIFFUSION AND ADAPTATION RELATING TO THE ANDEAN PACT COPPER PROJECT

| | |
|---|---|
| BOLIVIA | |
| COMIBOL: | Reconsideration of the Tasna Project: R and D for applying bacterial leaching to the marmatite concentrates and zinc tailings at Colquiri: considered application of bacterial leaching to copper sulphide marginal ore and chalcosite concentrates at Corocoro. Further projects relating to other techiques and minerals are being designed by the trained team. |
| IIMM: | Interest in bacterial leaching research particularly with respect to tin sulphides and reduced tin tailings. |
| Private sector: | Interest in applying bacterial leaching technology to copper sulphide ores and silver concentrates at various mine sites. |
| PERU | |
| CENTROMIN: | A second pilot plant is being planned for Toromocho using a SX-EW recuperation process instead of cementation on scrap iron; bacterial leaching is being considered at the industrial scale at Toromocho: bacterial leaching is being applied to in situ minerals at Cerro de Pasco. |
| MINERO-PERU: | Project development at Cerro Verde, with INGEMMET researchers in the areas of bacterial leaching of sulphide values from previously leached oxide heaps; leaching marginal sulphide ore and leaching sulphide concentrates. |
| INGEMMET: | Continued R and D on the Cerro Verde minerals with additional funding from OAS; research on dearsenicization of smelter feeds and small-scale applications of bacterial leaching within Peru. |
| Private sector: | Hochschild is developing a large-scale bacterial leaching project on optimized copper ore heaps at Pativilca; R and D on bacterially leaching silver concentrates is in progress carried out by a university microbiologist previously employed by CENTROMIN for the Copper Project. |
| TECHNOLOGY SUPPLIERS | |
| GTZ: | On basis of the success of the Copper Project is considering financial support for follow-up projects for both planning and project implementation to include equipment supply, training programmes and contracting of foreign experts. |
| Foreign experts: | Both experts have kept up links with the trainees and encouraged new ideas; the bacterial leaching expert later gave a training course at IPT, in São Paulo, Brazil. The diffusion effects of their participation requires further investigation. |
| CO-ORDINATING INSTITUTION | |
| Andean Pact: | Support for follow-up lines of action in biotechnology and technology development in the minerals sector of the Andean region. The Project's original designer and Co-ordinator is now participating in the planning of a similar project under the auspices of UNIDO in Chile. |

(2) INGEMMET has now built up a strong capability in the area of bacterial leaching evidenced by its "anticipative" applied R and D work on ore from MINERO-PERU's mine at Cerro Verde. Since the oxide zone at that site is now nearly depleted, it is planned to bacterially leach the remaining sulphide values, from the sulphuric acid leached oxide piles, and marginal ore from the underlying sulphide zone. The installed capacity of the solvent extraction plant may be adapted to recover the copper from the solutions. MINERO-PERU, lacking the complete capacity itself, is planning to contract experts from INGEMMET to work with its own personnel at the mine site to develop and apply the bacterial leaching technology. In addition, INGEMMET has been contracted recently by some small private mining companies to assess the leachability of various ores. INGEMMET is also carrying out R and D on the extraction of pollutant arsenic by bacterial leaching from smelter feeds.

(3) An R and D division was established within COMIBOL as a consequence of the Copper Project and applied research carried out by the trained team on the bacterial leaching of copper ore from Tasna. A pilot plant programme for Pailaviri was subsequently planned though not implemented. In addition, some more innovatory research was carried out on marmatite (zinc) concentrates from Colquiri. Although the results were positive the technology was not developed nor was the mine management informed of its potential as an alternative for recuperating marmatite from flotation tailings. Finally, it should be mentioned that the Special Project Division in Metallurgy, created in COMIBOL to carry out the Copper Project, has recently completed the following: (a) a feasibility study for the hydrometallurgical plant at the Corocoro copper mine (oxide leaching); (b) a prefeasibility study for polymetallic tailings at San Miguel; (c) a prefeasibility study for copper tailings at Telamayu; (d) a pre-investment study for the polymetallic tailings of Telamayu; (e) a feasibility study of the polymetallic deposits of Bolivar. None of the projects, however, are based on bacterial leaching.

(4) Finally, the private sector in both Bolivia and Peru has recently shown much interest in bacterial leaching. In Bolivia, owners of several undeveloped copper sulphide deposits are considering bacterial leaching technology as a low-cost investment technique in the context of an unstable political environment. In Peru, a former member of the CENTROMIN team is now directing the development of two bacterial leaching projects for a private company.

Summary of present state of bacterial leaching technology development in Bolivia and Peru

Through analysing the Andean Pact Copper Project, in terms of the scheme developed in chapter I (section 1.5) to categorize the requirements for technology development in bacterial leaching, it is possible to identify the strengths and weaknesses in each country's "capability framework".

The present state of technological capability accumulation in bacterial leaching in both Bolivia and Peru is summarized below; the salient features are noted in table 6 and related comments are made below following closely the structure of the Technological Capabilities Scheme for Bacterial Leaching Technology Development. *

Bolivia

It seems that the IIMM team has a basic knowledge of bacterial leaching techniques backed up by most of the elementary facilities, equipment and skill inputs required to carry out preliminary research. This knowledge would also seem to embody an awareness of current trends in the world minerals industry, particularly in relation to the flotation of tin, zinc and the main sulphide minerals and also the leaching of tin. IIMM seems to have established a reputation in both the public and private sector for doing reliable chemical analyses of minerals and mine water. IIMM has no microbiological expertise, however the University of La Paz has a microbiology faculty which is interested in industrial biology and starting research in bacterial leaching.

In addition, a former member of the IIMM and the trained Copper Project team is now teaching a course in bacterial leaching to engineering students at the University of Oruro. This may improve knowledge inputs for bacterial projects in the future.

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* See source material listed in annex IV.

Table 6. Summary of the state of bacterial leaching technology developmen

| Country and firm or institute | (A) Technical feasibility and geological evaluation | (A) Choice | (B) Evaluation of leachability of ore | (B) Design of parameters |
|---|---|---|---|---|
| **PERU** | | | | |
| CENTROMIN | Own several deposits where bacterial leaching could be applied including Toromocho and Cerro de Pasco. Have basic geological evaluation capability. | Demonstrated capabilities in selecting bacterial leaching as an additional process route, in conjunction with solvent extraction, at Toromocho and Cerro de Pasco. | Have proven capability. Own necessary equipment, instruments etc. Insufficient emphasis on microbial aspects and incomplete multidisciplinary team. | Demonstrated capabili extensive set of deta though encountered pr operation with mining limited extent of imp optimized system. |
| MINERO-PERU | Bacterial leaching is applicable at Cerro Verde and possibly (Michiquillay) and Andina. However, have difficulties in geological evaluation of existing oxide heaps to determine nature of remaining sulphide values. | Demonstrated capabilities in consideration of bacterial leaching as means to use installed industrial capacity of oxide hydrometallurgy plant. | Capabilities in oxide hydrometallurgy but not in bacterial leaching and lack microbiologist. | No demonstrated capab in the area of bacter |
| Private sector | Bacterial leaching applicable at Hochschild's Pativilca and possibly Southern Peru Copper Corporations's Toquepala and Cuajone mines. Small medium-scale mine applications require investigation (including applications to auriferous pyrite deposits). | Selection of bacterial leaching as additional process route for marginal copper and silver at Pativilca. Some small companies have awarded research contracts to INGEMMET. | Hochschild has basic equipment, knowledge of procedures and a microbiologist is included in the team. | Hochschild probably ha this area through the former CENTROMIN trai Copper Project. |
| INGEMMET | Geological knowledge of mineral deposits of Peru permits indication of potential sites for bacterial leaching application. | Demonstrated capability to carry out "anticipative" R & D and participate in companies' technical choice processes. | Have proven capabilities and basic equipment, though more precision instruments are required. Microbiologists and chemical engineers form main team. | Have capabilities to production firm in de parameters. |
| Universities | No demonstrated capabilities. | No demonstrated capabilities. | Microbiologists at San Marcos University, Lima, carrying out bacterial leaching research for private sector. | No demonstrated capabi |
| **BOLIVIA** | | | | |
| COMIBOL | Several dumps require evaluation. Need to resolve problem of dump evaluation. Future potential for bacterial leaching of marginal overburden when unexploited porphyry sulphide copper-zinc-lead-silver zone in south-west Bolivia is developed. | Poor choice capabilities demonstrated in Tasna and Pailaviri projects yet awareness at some management levels of potential of bacterial leaching for Bolivia. | Knowledge of basic procedures and own equipment except microscope. No microbiology input. | Basic knowledge demons parameters, but not of them or achieve scale |
| Private sector | Several small/medium copper sulphide deposits. Potential applications to auriferous pyrite deposits. | Interest in the potential of bacterial leaching for low cost investment development of small/medium mines. | No demonstrated capabilities. | No demonstrated capabi |
| IIMM | No demonstrated capabilities. | Interested and previously researched in bacterial leaching. | Have equipment and interested metallurgists but no current research experience in bacterial leaching. | No demonstrated capabi |
| Universities | No demonstrated capabilities. | Microbiology department interested in research programme in bacterial leaching. | No demonstrated capabilities. | No demonstrated capabi |



SECTION 1

the state of bacterial leaching technology development in Bolivia and Peru

| (B) | | (C) | (D) |
|---|---|---|---|
| f leachability of ore | Design of parameters for scale-up | Pilot plant, design and testing | Industrial scale design, implementation and optimization |
| ability. Own necessary uments etc. Insufficient obial aspects and disciplinary team. | Demonstrated capabilities to design extensive set of detailed parameters though encountered problems of co-operation with mining engineers which limited extent of implementation of optimized system. | Seven pilot heaps at Toromocho with scrap iron recovery process, inadequate organization of personnel at pilot plant and insufficient ongoing R & D, especially in bacterial leaching. | Provided input to Kaiser feasibility study for development of main Toromocho project in area of bacterial leaching of marginal overburden. Are working on process optimization and require microbiological inputs and closer co-operation with geologists and mining engineers in production sector. Are operating from Cerro de Pasco industrial plant for recovery of copper from dumps and disused mine. (Reduces pollution by the natural leaching process.) |
| n oxide hydrometallurgy erial leaching and lack | No demonstrated capabilities in the area of bacterial leaching. | Constructed pilot heap with INGEMMET but never began bacterial leaching operations. | At Cerro-Verde there exists unutilized installed capacity of oxide leaching piles, solution distribution systems and pumps and of solvent extraction electrowinning plants and related production experience. Potential exists for adapting these capabilities to bacterial leaching of marginal sulphide ore. Requires formation of multi-disciplinary team, some training and closer co-operation with INGEMMET. |
| basic equipment, knowledge and a microbiologist is e team. | Hochschild probably has capabilities in this area through the participation of former CENTROMIN trainee in Andean Copper Project. | No demonstrated capabilities. | No demonstrated capabilities, though no information available on activities of Southern Peru Copper Corporation. |
| apabilities and basic equipment. recision instruments are obiologists and chemical ir main team. | Have capabilities to participate with a production firm in designing scale-up parameters. | Capabilities to provide ongoing R & D input to a pilot plant programme though not utilized. | Capabilities to provide ongoing R & D input at the mine and plant site. |
| ists at San Marcos University, g out bacterial leaching private sector. | No demonstrated capabilities. | No demonstrated capabilities. | No demonstrated capabilities. |
| basic procedures and own ept microscope. gy input. | Basic knowledge demonstrated of the parameters, but not of how to obtain them or achieve scale up in Tasna study. | Designed Pailaviri pilot plant, however was not implemented due to inadequate evaluation of mineral content and social context. | No demonstrated capabilities. |
| ated capabilities. | No demonstrated capabilities. | No demonstrated capabilities. | La Joya industrial dump bacterial leaching operation worked very inefficiantly (10% recuperation levels); never optimised nor was the microbiological component, later identified by IIMM, realized by the operators. |
| ent and interested metallurgists ent research experience in aching. | No demonstrated capabilities. | No demonstrated capabilities. | No demonstrated capabilities. |
| ated capabilities. | No demonstrated capabilities. | No demonstrated capabilities. | No demonstrated capabilities. |



SECTION 2

IIMM, in part based on previous unutilized research, recognizes the potential of applying bacterial leaching in Bolivia and is aware of what would be the basic requirements to carry out a project. What is needed is both training and involvement in an industrial project. This would enable IIMM, in conjunction with the universities, to provide a capacity to evaluate the leachability of a given ore and carry out problem-solving and ongoing R and D during pilot plant programmes and industrial-scale operations.

In the private sector the existing relevant capabilities include a basic geological evaluation capacity and an awareness on the part of some managers of medium-sized mines of the potential of bacterial leaching. Major problems include: the lack of direct, and perhaps collective, fund allocations to capability accumulation activities like local R and D, technical training programmes and technology search. However, there is a Medium-Scale Miners Association which has shown an interest in bacterial leaching and has good information collection facilities and knowledge of technical advances and market trends in the minerals industry.

COMIBOL has some facilities, equipment and skills relevant to carrying out activities for general process route selection but it lacks information, training, managerial support and funds to develop these ideas into worthwhile alternatives. * The evidence indicates that dumps at COMIBOL's mines contain much unexploited mineral wealth. However, its geological evaluation procedures are basic and the wooden shaft block technique - a time-consuming, labour-intensive method which is the only available method it has to evaluate dumps reliably and at depth - needs to be utilized and diffused within and outside of COMIBOL. **

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* This capability is more developed in the area of tin extraction and recovery than sulphide mining and processing

** The widespread application of the wooden shaft block technique would stimulate employment, the maintenance costs of which could be paid for by the gains from exploiting the evaluated dumps. A superficial examination of data for dump reserves indicates the feasibility of this.

The Division of Special Projects in Metallurgy, COMIBOL's research department, has no organized information storage and retrieval system and a poorly stocked library. However, the need is recognized, the facilities exist and one employee even has the task of librarian. Again there is a problem of lack of finance and co-ordination.

COMIBOL lacked a multidisciplinary team throughout the project's development. Although it included metallurgical and chemical engineers and management for most of its duration, it did not include sufficient inputs from microbiologists, mining engineers or geologists at the mine sites.

No proven capacity exists within the firm to assess the social implications of applying bacterial leaching to existing mineral dumps. However the miners, including the women dump workers, are very well organized and could make essential contributions if management were to accept their participation in project decision making.

There were not sufficiently efficient communication channels nor reliable infrastructure or facility of access within the COMIBOL capability framework. This restricted the extent to which R and D personnel could work with the production sector. However, the Division of Special Projects in Metallurgy has good international contacts with both foreign experts and assistance organizations which could be followed up, given support from higher management, and used beneficially in the planning of future bacterial leaching projects.

COMIBOL has adequate precision instruments to carry out chemical analyses although some spare parts are missing and the equipment is often unutilized due to lack of demand. COMIBOL also has most of the basic equipment needed for bacterial cultivation and maintenance and flask and column tests.* However, the knowledge, skill and experience necessary to carry out these activities and optimize the leaching processes are presently lacking. Some personnel, trained during the Copper Project and now outside COMIBOL, could, and indeed are willing to provide some of these inputs anew. But again, further training, fund allocation and the selection of feasible projects is required.

COMIBOL, through the assistance to the Copper Project, obtained the necessary bacterial leaching pilot plant equipment. However, the team has no proven capacity in either the provision of reliable parameters for scale up or optimizing bacterial activity and yield; it did display a knowledge capacity in the area of leach system design and solution management. However, this was

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* The equipment received specifically for the bacterial leaching project by Bolivia included the following items, accessories and spare parts:

Laboratory

- Variable speed agitators with flask carriers and flasks
- Automatic print out titration equipment and pH meter
- Precision balances
- Demineralizer
- Water distiller
- Drying oven and heating elements
- Incubator
- Pressure regulator
- Magnetic stirrer and hot plate
- Portable autoclave
- Bacterial filters
- Ball mills
- Bio-oxidation system
- Crusher, pulverizer and grinding plates
- Flow meters and indicators

Pilot Plant

- 4 highly resistant plastic pumps (1,500 rpm, 1 in. x 1 in.)
- 2 highly resistant plastic pumps (1 1/2 in. x 1 1/2 in.)
- 4 magnetic starting motors
- 600 $m^2$ of PVC sheeting
- 4 centrifuge plastic pumps
- 4 rotators

Source: Bolivian Project Manager, Evaluación de las Actividades Realizadas por Bolivia en los Proyectos Andinos de Desarrollo Tecnológico en el Area del Cobre (J/GT/107), 7 December 1981) not accompanied by an informed decision-making capability with respect to either progression to the pilot plant stage (as, for example, in the case of the Pailaviri project), or the technical and economic feasibility of specific planned industrial operation (for example, the Tasna project).

Finally, no mechanisms were created to diffuse the bacterial leaching technology developed either within or outside of COMIBOL. Thus, in the absence of fund allocation by management or assistance organizations to enable work to continue in this field, the existing capability framework may not receive the strengthening it requires for the future development, implementation, operation and optimization of bacterial leaching projects in Bolivia.

Peru

During the development of the Copper Project, INGEMMET has built up probably the strongest and most consistent set of bacterial leaching technological capabilities within the subregion. These capabilities are mainly concentrated in the areas of pure and applied research and to some extent in project formulation.

Since geological, extractive matallurgical, chemical and microbiological research is carried out within the same institute, and the institute is located in the campus of the principal engineering university of Peru, Universidad Nacional de Ingeneria (UNI), a potential evidently exists for building up multidisciplinary teams. For example, a capability exists to assess the general possibilities of applying bacterial leaching in Peru through geological knowledge of the types of mineral deposits which exist in the country and metallurgical and microbiological knowledge of their suitability for leaching. However, these capabilities have yet to be combined effectively to bring about technical change activities in this area.

At present there is a team comprising one chemical engineer, one microbiologist, technical assistants and a visiting research chemist from the Federal Republic of Germany. One researcher received training in a Belgium university where he investigated the leachability of Cerro Verde's ore. The equipment, which is very basic, was acquired by INGEMMET independently of the Copper Project, and includes microscopes, an incubator, a simple agitator, flasks and columns. However, the team now feels their research has advanced sufficiently to warrant higher precision equipment for more detailed research into leaching mechanisms and optimization procedures.

Furthermore, the publication of research articles, invitations to international conferences, contract research for small private mining companies and the proposed co-operation with MINERO-PERU at Cerro Verde indicate that INGEMMET, through the Copper Project, not only has developed a reputable capability in bacterial leaching but has also linked it with the requirements of the production sector. This also demonstrates an important decision-making capability in relation to the independent anticipation of a company's future needs and the design and presentation of a feasible collaborative project at the appropriate time

However, a current lack of fund allocation to bacterial leaching research within INGEMMET and its new emphasis on contract research for industry may limit the amount of basic and anticipative research that can be carried out.

Similarly, while there is a basic knowledge of the international state of the art of bacterial leaching this needs to be augmented by information inputs. However, bibliographies and journal subscriptions are limited and there is no funding currently available for participation in conferences or visits to international centres of expertise.

Finally, INGEMMET has the capabilities required to provide an ongoing research and problem-solving input at both the R and D pilot-plant and industrial stages to the mineral companies of the subregion; but because it is an R and D institute - without production facilities - its set of technological capabilities in the area of bacterial leaching will always be complementary.

In the universities very little research is taking place in biotechnology in general and bacterial leaching in particular. The microbiologist who worked with CENTROMIN is continuing bacterial leaching research in the University of San Marcos using ores from Hochschild's mine at

Pativilca. Biotechnnology research in Peru is mainly related to the production of pharmaceutical products like antibiotics, vitamins and amino acids. The extent to which these research programmes could be extended to include, say, genetic engineering research into thiobacillus, still has to be investigated.

In the private sector in Peru the main capabilities in bacterial leaching seem to be concentrated in Hochschild where multidisciplinary teams are being built up to develop projects in the area of bacterial leaching copper and silver. These teams are working at the mine site. They are being directed by the former head of R and D at La Oroya who was trained in the Copper Project and is the principal author of most of CENTROMIN's reports. The capabilities of the Southern Peru Copper Corporation were not investigated although the geology and volume of its porphyry deposits at Cuajone and Toquepala suggest a great potential for a waste and marginal ore leaching programme. Finally, some small companies have demonstrated a knowledge capability in bacterial leaching through contracting INGEMMET to make some preliminary assessments of the leachability of some of their ores.

MINERO-PERU at Cerro Verde has the advantage of an existing capability at the R and D, pilot plant and industrial scales in oxide hydrometallurgy. They have a basic geological evaluation capacity and knowledge capability regarding the type, tonnage and composition of their in situ sulphide reserves and the implications for process route selection. However, they have no developed capabilities - in terms of either equipment or expertise - to undertake systematic sampling of sulphide mineral reserves in their oxide leaching heaps; nor are funds presently available to remedy this.

In MINERO-PERU there is a small R and D department, the Division for Design, Technology and Control of Production. Within this department there is expertise and equipment in the area of oxide leaching. However, there are neither microbiologists nor the necessary instruments and facilities to research bacterial leaching processes. Furthermore although there are analytical facilities for evaluating the composition of leach effluents there is no proven capacity to analyse the biological characteristics of solutions. This could be remedied with little marginal cost and effort.

There is a limited knowledge of the potential of bacterial leaching or the general state of the art. However the recently appointed head of the R and D division, who was trained through the Copper Project, is supportive of bacterial leaching; while a metallurgist, formerly of INCITEMI and trained in the Copper Project, has a proven capacity in idea generation and project formulation and attended a recent biometallurgy conference in April 1983 in Italy. MINERO-PERU has no proven capability in bacterial leaching at the pilot plant stage; it designed and constructed an experimental heap at Cerro Verde with INGEMMET but this was never operated.

In conclusion, although MINERO-PERU clearly has no specific capabilities in bacterial leaching itself, it could adapt its oxide hydrometallurgy capabilities to encompass large-scale sulphide leaching. Minor changes of the solvent extraction pro ss would be required to deal with copper sulphate solutions from bacterial leaching. If the surface of the oxide heaps could be rendered impermeable then they could provide the base for sulphide heap leaching and existing solution channels, distribution systems and access routes could be used.

Finally, the possibility of mixing solutions should be investigated since sulphide leaching of marginal ore may compensate for undercapacity at the solvent extraction stage while the oxide zone is being terminated or solutions from the leaching of other reserves of oxide ore, owned by MINERO-PERU, are sent to Cerro Verde for treatment.

CENTROMIN has the advantage of being able to build upon the existing capabilities of the former Cerro de Pasco Corporation which had already established a R and D division at La Oroya, the centre of its mining and processing operations.

CENTROMIN has a basic geological evaluation capability with back up support in mineralogical and chemical analysis. The Department of Special Projects was established within the Division of Metallurgy Research at La Oroya to carry out the Andean Pact Copper Project. It has all the basic facilities, equipment and instruments necessary for a R and D and pilot plant programme in bacterial leaching since CENTROMIN was one of the principal recipients of equipment in the Copper Project.* However, there is no longer a multidisciplinary team devoted to bacterial leaching now that the Toromocho pilot plant project has been stopped. This means that despite some microbiological research being carried out by metallurgists, some of the equipment remains unutilized and the possibilities of microbiological optimization remain unexplored.

What is impressive about the CENTROMIN set of technological capabilities is the adaptation of standard research methods to suit their own particular needs. For example, research was carried out on the comparison of local and foreign bacterial activity in the Toromocho leaching environment and on continuous bacterial cultivation. The effect of rainfall on pH and

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* This equipment included the following items and relevant accessories and spare parts:

| Laboratory | Pilot Plant |
|---|---|
| Variable speed agitators with flask carriers and flasks | 4 highly resistant plastic pumps (1,500 rpm) |
| Demineralizing equipment | 4 starting motors |
| Water distillers | 600 m2 of PVC sheeting |
| Drying oven | 4 centrifuge plastic pumps |
| Sterilizer | 4 rotators |
| Incubator | Krupp solvent extraction-electrowinning pilot plant |
| Thermostats | |
| Counting chamber | |
| Pressure regulator | |
| Magnetic stirrer | |
| Hot plate | |
| Portable autoclave | |
| Centrifuge | |
| Bacterial filters | |
| Flow meters | |
| Thermometers | |
| Micropressure balance | |

CENTROMIN already had its own microscopes and pH meters. In addition electrochemical equipment at La Oroya includes a potentiostat, a function generator, a potential meter and a recorder. (Source: Bolivian Project manager, "Evaluación de las Actividades Realizadas por Bolivia en los Proyectos Andinos de Desarrollo Technológico en el Area del Cobre" (J/GT/107), 7 December 1981).

bacterial activity was evaluated and large column leaching systems were devised to simulate scale-up conditions. Furthermore, these capabilities to carry out research programmes more advanced than were taught to the teams in the technology transfer process are either incorporated in personnel presently working at La Oroya and Cerro de Pasco or accessible through the many technical papers written during the project as well as the detailed procedure manual that is being prepared.

An awareness of the importance of bacterial leaching to CENTROMIN's operations has been demonstrated by engineers and management. This is evident from the following:

(a) The important input that the Department of Special Projects made to the recent Kaiser Engineering Company prefeasibility study for the development of bacterial leaching at the planned industrial-scale project of Toromocho;

(b) The current plans for a new pilot plant project, based on the experience of the previous one, using the Krupp solvent extraction plant instead of cementation on scrap iron metal recovery;

(c) The participation of the Head of the Department of Special Projects in a six-week UNEP training course in the Microbial Leaching of Metals from Ores, held during May and June 1982, based at the USSR Academy of Sciences.

CENTROMIN demonstrated less developed capabilities in the area of scaling up. This was mainly due to its failure to co-ordinate its research programme with the activities of the mining engineers at the Toromocho site. Similarly the geology division was not included in the Project. Since the team at La Oroya have a limited geological knowledge particularly of the mineralogy of the company's reserves, the possibility of applying bacterial leaching to other suitable ores may be overlooked. In addition CENTROMIN did not fully develop technological capabilities at the pilot plant operation stage. There was very little ongoing R and D and no microbiological input; while inadequate organization at the plant site inhibited ongoing optimization and production process improvement.

Finally, although CENTROMIN has an economically efficient industrial operation at Cerro de Pasco this does not necessarily indicate a complete set of capabilities at this stage. This is because the mineral reserves are in situ and leaching systems dumps, that is, the systems are not constructed to optimize the process.

In summary, CENTROMIN has built up an important set of utilizable technological capabilities in bacterial leaching. However, the following weaknesses in its capabilities are apparent:

(a) The failure to build up a multidisciplinary team which includes the participation of geologists, mining engineers and microbiologists;

(b) The failure to achieve close co-operation between its R and D and production divisions;

Consequently engineers and management are not sufficiently aware of the potential of bacterial leaching.

The preceding summary is based on an analysis of bacteria leaching technology development in Bolivia and Peru through the Andean Pact Copper Project. This analysis revealed that in each country the problems and achievements observed could be explained not only in terms of initial constraints and advantages, or standard obstacles to development (such as the alienation of R and D from industry or the "brain drain" phenomena), but also in terms of the technology policy, the ways in which it was implemented and the extent to which requirements were met for technological capability accumulation in the area of bacterial leaching.

The analysis reveals some limiting and stimulating factors to achieving technological progress in bacterial leaching and implications for policy. The more important of these policy implications are discussed in the next section under three headings: linking research with production in bacterial leaching; the benefits and limitations of technology transfer in bacterial leaching, and the social context of bacterial leaching applications in the minerals industry.

## 2.2 Suggestions for project policy in bacterial leaching

The Technological Capabilities Scheme for the Development of Bacterial Leaching Technology (chapter I) is a basis for the formulation of policies for bacterial leaching projects. The remarks below complement the Scheme.

The problems and achievements of the Copper Project were analysed in terms of seven pertinent sets of technology policy issues. These were: (i) relations between research institutes and production enterprises and between research and production within firms; (ii) subregional co-operation; (iii) the participation of foreign experts and the transfer of technology; (iv) turnover of personnel; (v) the consolidation of technological capabilities and diffusion of the technology; (vi) technical and practical difficulties; (vii) the social context of the technology application.

### 2.2.1 Linking research with production in bacterial leaching

The research showed that processes of technical change and innovation in the minerals industry, when viewed at the project level, are highly complex. In the case of bacterial leaching, the biological and chemical processes function as part of a system which involves geology, hydrogeology, geography, physics, engineering and economics as well as social relations of work and management. For this reason the preparation, design and co-ordination of such projects requires the participation of technically informed personnel, with production experience, in addition to researchers, policy makers and planning managers.

Technical change and innovation processes in the bacterial leaching of minerals were not observed to be research-initiated. As the Capabilities Scheme of section 1.5.2. indicated, multidisciplinary teams, that include production personnel as well as researchers, need to work in close co-operation right from the beginning. These projects require initial inputs from both geologists and microbiologists; co-operation during the design and implementation phases between metallurgical and chemical engineers on the one hand and miners and mining engineers on the other; and R and D must be an ongoing activity throughout the preparation and operation of the project. For example, a geological evaluation must be carried out to determine the amount of copper that can be extracted, the characteristics of the mineralogy and the nature of the rock material. These results need to be interpreted by a metallurgist to determine the implications for technology applications and combined with the findings of microbiological field-work to evaluate the potential of applying bacterial leaching. The field-work should consist of analyses of the biological and chemical characteristics of local mine water, assessments of the biological activity of indigenous bacteria and a microbiological investigation of the leachability of the ore under consideration. It is evident that these tasks should be carried out in close proximity to, and in co-operation with the production sector; particularly since the leaching bacteria work best in their indigenous environment and the characteristics of mine water may change when transported. However, the cases of COMIBOL and CENTROMIN demonstrated that R and D undertaken by the firm, appropriate project selection and relevant research are not sufficient to ensure the industrial applications of the optimized technology. The success of any leaching programme also depends on whether the company's mining staff extract and dump the mine waste according to the parameters developed by the multidisciplinary research team, which will be composed principally of metallurgists, microbiologists and chemists. Links have to be forged between the disciplines of metallurgy and mining.

This poses something of a challenge for most mining companies since their departments usually work autonomously and interdepartmental communication is usually weak and often non-existent. For this reason management should be included early on in a bacterial leaching project since their support will be instrumental in bringing about the structural changes necessary to set up multidisciplinary teams and releasing production and R and D staff for training. This includes management at the mine site as well as at company headquarters since they often have decision making freedom and need to be aware of the alternative process routes available and the necessary special construction and operation procedures associated with bacterial leaching industrial systems.

Management will need to be convinced of the potential of bacterial leaching for each particular mine since every additional technical change activity carried out to achieve optimization - for example, strain selection, nutrient addition, preliminary crushing, ground preparation, heap design, etc. - represents an additional cost which, in the absence of standardized cost structures, requires its own justification to obtain funding because there are no standard procedures or cost structures for bacterial leaching operations. Furthermore, optimizing bacterial leaching is an ongoing activity since mineral content declines, particles decrepitate, solution compositions change and the bacteria growth needs to be continually stimulated. So again management support will be needed to ensure that funds and sufficient personnel are allocated to the operative plant to enable an ongoing R and D and engineering improvement programme to be effective.

The analysis of the Andean Pact Copper Project illustrated the influence of decision makers, and particularly the importance of "entrepreneurial" characteristics, for the possibility of developing this "unconventional" technology. Indeed, every case of intended application of bacterial leaching in Bolivia, Peru and Chile had a crucial example of one manager's enthusiastic commitment to the technology.

Most mining companies do not have microbiological facilities, and a genetic engineering programme would probably be beyond the scope of all but the large transnational enterprises. Therefore, both research institutes and universities may have an important role to play in complementing the capabilities of mining companies in bacterial leaching projects. However, in the case of the larger mining companies, the possibilities of expanding medical facilities, where they exist, to carry out bacterial leaching research should be explored.

The examples of CENTROMIN and INGEMMET illustrated the delicacy of the task of trying to link microbiological research carried out in an institute away from the production site with the more metallurgy-oriented research carried out at the firm when the latter is not fully aware of the potential offered by microbiology for optimization. However, the cases of developing co-operation between MINERO-PERU and INGEMMET, CODELCO and INTEC and Disputada and CIMM show that if a company is determined to carry out an efficient leaching project, and is convinced of the potential for bacterial optimization, there is a need for microbiological inputs which can be best fulfilled by a local research institute.

This was further supported by the observation that a transnational corporation operating in Chile had found its own organizational structure, which contracted out research to a subsidiary in its home country, inappropriate for carrying out an optimized bacterial leaching project. This is due to the already-emphasized site-specificity of bacterial activity, the constraints on ore and mine water transportation (which means research carried out abroad, as well as being unnecessarily costly, produces unreliable results), and the need for continuous inputs of local knowledge which are generally best provided by personnel whose educative and professional experience has a large "local" element.

All the examples of research institutes and firms working together indicate that if the varied input requirements for a bacterial leaching project are to be effectively combined then researchers need to make frequent and extended visits to the mine site and work alongside production personnel.

Finally, and following on from this, the case of the evolving though only recent co-operation between INGEMMET and MINERO-PERU indicated the benefits arising from allocating funds and facilities to enable research institutes to undertake <u>anticipative</u> bacterial leaching research on ore from local mines. On the basis of such research, project proposals can be presented to be developed in conjunction with the operating enterprise. This is also a means to inform mine management who, due to immediate production problems, are often unaware of the potential benefits of including bacterial leaching as an additional process route.

### 2.2.2 <u>The benefits and limitations of international technology transfer in bacterial leaching</u>

Throughout its duration the Andean Pact Copper Project illustrated both the benefits and limitations of the international transfer of technology-related inputs, both from developed countries and between developing countries, for local technological capability accumulation in bacterial leaching.

### 2.2.2.1 Subregional co-operation

The Copper Project indicated that while there are obviously a vast number of technical problems of mutual interest their resolution through co-operative endeavours is subject to many constraints. Variation in composition and amount of reserves, differing costs of production and levels of technical advance as well as differences between each country's state of political and economic development, mean that joint activity has to be carefully planned, especially where, as in the case of bacterial leaching, there is no precedent for co-operation. However, it can be argued that these differences impose more constraints on co-operation in the area of minerals marketing - the traditional sphere for intercountry endeavours - than on technical projects. Annex III gives some more details of the characteristics of the minerals sector of Bolivia and Peru.

Unilateral marketing action on the part of the mineral-producing countries is a more radical type of endeavour. To be effective such action requires the participation of the majority of exporting countries. It involves greater political commitment and a higher level of decision taking at the country level. It can be argued also that, despite nationalization, the developing countries do not have sufficient control over their mineral industries (particularly in relation to technological aspects and project financing) to weather out possible international repercussions. Furthermore, the costs of such an operation may be prohibitive, it has been estimated that any copper stabilization scheme would require at least US$ 3 billion to be effective [97]

In contrast, the advantage of collective strategies in the sphere of production technology stems from their flexibility. Such projects can be designed by the developing countries themselves to include any number of countries and can involve varying degrees of integration.

The scope for such co-operation is rooted in the fact that mineral zones do not respect political boundaries. So, although every mine site is a special case and the structure of each country's mineral sector is different, there will exist mutual mining and metallurgical problems in certain mining regions stemming from their shared physical base.

However, the necessity for commercial secrecy obviously places limitations on the extent to which technical information can be exchanged; although the Andean Pact Copper Project clearly demonstrated the advantages of joint seminar courses and training programmes. Apart from achieving economies of scale in contracting world experts, such meetings, if well co-ordinated, enable the discussion of specifically chosen metallurgical problems. Problem-solving, through joint discussion, laboratory and field-work, however, seems dependent upon the establishment of an informal atmosphere of trust, mutual support and the pooling of ideas.

For this reason, it is important, for example, that all the participants stay in the same hotel and that meetings last for extended periods of time (i.e., two weeks to one month). Furthermore, such international encounters should involve visits to mine sites, if possible, in the countries where the participants work. It is essential that imbalances, through focusing only on the problems of the host country, are avoided. The sharing of technical reports and literature reviews were also very advantageous in the Copper Project. However, such activities need co-ordination. So bodies like the Andean Pact, or at least a subregional co-ordinator, can play an important role in the collection of information and its distribution to all interested groups.

Due to subregional geological similarities, which give rise to shared mining and metallurgical problems, there is much potential for subregional consultancy work in the area of bacterial leaching. For example, the more experienced CENTROMIN and INGEMMET teams could have advised the Bolivian team while groups from Peru, Bolivia and Chile could undertake consultancy in countries like Colombia and Brazil which are just developing their mineral industries and have plans to develop bacterial leaching technology. Most important, correlative leachability analyses carried out in countries like the Andean Group, which have similar environmental conditions, would be much more reliable and cheaper than ones carried out thousands of miles away in the facilities of some developed-country institute or firm. These activities could be carried out either through direct contract or as part of a co-operative programme.

Such activities were not carried out in the Copper Project - mainly due to a lack of policy initiative than to a lack of technical or political feasibility. There was a tendency in the Copper Project to formulate detailed policy for the transfer of technology from the developed countries but to expect subregional co-operation to happen automatically.

The most effective type of technical co-operation, at least at the initial stages when mutual trust has to be built up, is probably informal discussion amongst researchers and engineers. However, the formal bureaucratic and exclusive nature of intercountry co-operation meetings, where often political representatives rather than technical experts are present, are not conducive to the real joint solution of metallurgical problems that particular researchers may encounter.

Clearly there is a need to open up decision-making processes, to have frequent and extended intercountry meetings, to move projects around the geographic sphere of the co-operative agreement and perhaps to employ a subregional co-ordinator if technology development in bacterial leaching is to be enhanced by subregional co-operation.

Finally, on this point it should be emphasized that effective technology transfer processes between developing countries are often more gradual than originally envisaged, especially where no precedent exists. This means that the dynamic for their consolidation and continuation needs to be built into related policy so that the process can continue after projects officially end. For this reason it may be beneficial to obtain support at the government level and formulate and obtain detailed long-term policy commitments.

#### 2.2.2.2 Technology transfer from the developed countries

Since the majority of commercial bacterial leaching operations are suboptimal dumps, no general models exist upon which developing countries can base the design of optimized systems. The extent to which developed-country experts can contribute to technology development in bacterial leaching is thus limited by an experience which is mainly confined to solution management rather than system design or bacteria improvement. This explains why in the industrial field the majority of experts are chemical engineers. In contrast, most of the work on the microbiological aspects of leaching has been carried out in research institutes or universities by microbiologists with little focus on the engineering problems associated with scale-up to industrial application.

While there are a few specialized international experts in bacterial leaching their role mainly has been to assess the leachability of ores on a short-term contract basis for large mining companies. Their involvement in technology transfer programmes, as evidenced by the Andean Pact Copper Project, would thus tend to be biased towards the research rather than the industrial stages of bacterial leaching technology development.

These discrepancies in the structure of bacterial leaching technology development in the developed countries help to explain why particular emphasis must be placed on microbiology, particularly at the industrial level, in technology transfer programmes. Similar reasons can be given for the necessity to emphasize mining engineering and geology in project policy for bacterial leaching in developing countries. Since dump leaching systems are faits accomplis, in the sense that they have already been built and it is very expensive to dismantle and rebuild them, the co-operation of mining engineers to implement parameters for optimal construction is not relevant. Similarly, most dump and tailing reserves in the developed countries have been either subject to geological evaluation or their mineral content has been reliably estimated since stricter controls were enforced and more detailed analyses undertaken at the time of mining and dumping.

These limitations of developed countries as suppliers of bacterial leaching technology create a special challenge to developing countries. This is because although all the areas mentioned are important sources of technology, they have to be individually sought out, combined and then adapted, alongside inputs of local origin, to the specific requirements and conditions of the proposed application. A well planned and technically informed policy approach to bacterial leaching technology development is thus imperative if bacterial leaching projects are to be effectively designed by, and optimally operated in developing countries.

While foreign experts can effect a real transfer of technology through training programmes accompanied by site visits, their own economic constraints (for example, the necessity to obtain more contracts) and their different conception of technology generation (based on their developed country experiences) can adversely affect technology transfer unless the project is well and continuously co-ordinated. For example, in the Copper Project, a four-phase training programme, for completion in two years, was presented by the technology supplier which included: (i) an introduction to bacterial leaching R and D; (ii) an evaluation of the leaching potential of various mines; (iii) the design of leach dumps and operation procedures; (iv) the continuous evaluation of the leaching process. Eight years later the expert was still recommending continuance of the role of his institute as a consultant and the monthly sending of progress reports and data to him for analysis.

It emerges that an essential capability is to know to what extent and in what areas information should be sought, from which experts it can be obtained and at what stage the co-operation should be terminated. This means that the co-ordinators of a bacterial leaching project need to have a sound technical knowledge, and sufficient time to monitor the transfer process and they must be in close contact with project personnel. They should be able to criticize and expand on the experts' proposals and recommendations and challenge the experts where necessary on the various issues arising from their reports.

It emerged in the Copper Project that a greater amount of "real" technology transfer was realized by the university-based scientist. He kept up contacts with individual researchers and was apparently always available to advise on problems during the training seminars. The technology he transferred formed the basis for the adaptation by the Bolivian and Peruvian teams of bacterial leaching to other metallurgical problems; for example, relating to marmatite, silver and arsenopyrite leaching. It is also interesting to note that the training which the INGEMMET researcher received at the University of Loire in Belgium through the OAS was instrumental in building up the technological capabilities required for the anticipative research undertaken on the Cerro Verde ore. Indeed, there is much evidence to indicate that universities may be a crucial source of technology for developing countries planning bacterial leaching. This is especially true when one considers that it is here where the majority of genetic engineering, microbiological and reactor design research is being carried out. Developing-country mining companies may thus be advised to forge links with universities specializing in bacterial leaching and not just mining companies or contract-oriented research centres. The potential of technology transfer from developed-country universities specializing in genetic engineering has also been noted in relation to other biotechnology applications. 93/

The microbiological assessment of the leachability of ore is an important and integral task during the initial stages of a bacterial leaching project. Therefore related training should form a priority in any technology transfer programmes; especially since sending samples abroad are costly, results are unreliable and the distance between the mine site and the institute or expert supplying the know-how reduces learning opportunities. These testing procedures could be learnt from experts in universities, perhaps through sending grant-supported students for short training periods or student exchange programmes. It should be realized that it is often students or technicians at the technology suppliers' base who carry out such testing and not the experts themselves.

Negotiation and the obtaining of information requires personal qualifications and confidence as well as a basic knowledge of the technology backed up by information provided by local engineering and consulting groups. All recommendations made by foreign experts need to be thoroughly checked. And it should be remembered that foreign bacteria are not "better" than local bacteria. Using indigenous bacteria and local mine water is a first step to optimization. Indigenous bacterial strains will have to be adapted over time to the particular chemical and biological characteristic of the local water and rocks - including the molybdenum and silver contents which are typical of the Andean porphyry bodies.

While it is important to know when to terminate a technology transfer agreement, decision makers also should be in sufficiently close contact with the working teams to know whether or not the technology has been assimilated by the recipients and how an ongoing assimilation process can be accelerated. The analysis of the Copper Project indicated the necessity to include in the project policy mechanisms to ensure technology assimilation took place. For example, junior members of the technology supplier's institution could stay on to assist teams after consultancies, firms could undertake internal training courses, and technical knowledge could be consolidated and stored in accessible reports and manuals.

The extent to which technology is assimilated also depends on the technology recipients' existing capabilities and the extent to which they organize themselves to absorb these new inputs. For example, a mining company's medical facilities could be expanded to include bacterial leaching research; and, when trainee teams visit industrial plants each person could be responsible for obtaining specific information which later can be combined to accelerate the group learning process.

Finally some comments can be made about aid supply and technical and financial assistance.

The Copper Project illustrated the importance of obtaining finance for long planning periods for projects in bacterial leaching. This was enabled through untied assistance from the IDRC in Canada. These planning phases should include visits to the technology suppliers' bases and industrial bacterial leaching operations, surveys of potential sites of application, evaluations of the existing capabilities of potential technology development and, if appropriate, the negotiation of further financial and technical assistance for the development of the project itself. Assistance in negotiation and transfer procedures needs to be well co-ordinated to avoid delays and errors. For example in Bolivia, the chosen team was released from its usual duties to work on the Copper Project over a year before the delayed equipment arrived and funding for training was available. A "shopping list" approach by suppliers of technical assistance, as was adopted in the Andean Pact Copper Project, is inappropriate and will tend to inhibit the utilization of local technical inputs unless it is accompanied by policy aimed at developing capabilities in technology search, technical choice and negotiation procedures.

Thus, while the principle of untied assistance is very important for a particular project in a new area like bacterial leaching, it probably needs to be accompanied by policy mechanisms to ensure engineers and management have the necessary information to make optimum decisions, that is, policy or guidelines prepared by the recipients themselves.

### 2.2.3 The environmental and social context of bacterial leaching applications in the minerals industry

The research undertaken on the Andean Pact Copper Project indicated that people are either instrumental in the development of bacterial leaching projects or affected by its application. These issues were dealt with in terms of pollution effects, the turnover of personnel, the consolidation and diffusion of technological capabilities and existing problems of resource use and social relations at work. None of these issues receive adequate treatment in either the policy of the Andean Pact Copper Project or in the general literature.

The leaching bacteria themselves are not known to be toxic to humans. However, the environment in which they flourish (and which they help create) - highly acidic mine water - is highly pollutant if it is permitted to enter drainage waters. The creation of these acidic waters happens naturally in the mine environment where the leaching bacteria are ubiquitous. Therefore, one important advantage of the controlled application of bacterial leaching technology is the prevention of this pollution through the recovery of the dissolved metals. Indeed in some cases it may be feasible to recover dissolved metal ions solely to prevent metal and acid pollution rather than for their intrinsic economic value. However, this also implies that solution losses from the leaching circuit are highly dangerous. Ground surfaces should therefore be well prepared and information obtained about underlying soils and hydrogeology.

It is difficult to estimate the savings bacterial leaching could offer through the prevention of pollution, especially since many developing countries have no or few pollution regulations. However, the Governments of Bolivia, Peru and Chile spend thousands of dollars every day adding chemicals to the water supplies of their major cities to treat the acidic and metal-rich effluents entering the major servicing rivers from mining regions in the mountains above. And the prevention of such acidic pollution is one of the principal reasons for the implementation of bacterial leaching and metal recovery projects at Cerro de Pasco in Peru and Los Bronces in Chile. The analysis of the Copper Project indicated the fundamental input that technical knowledge makes to technology policy formulation and project planning implementation and co-ordination. The Project's Co-ordinator was a metallurgist who had direct production experience as well as expertise in technology policy formulation. Although he was based in the Andean Pact offices, he was able to make links directly with the firms, encourage the teams, resolve problems and co-ordinate the technology transfer process. Based on his evaluative research of the technology suppliers in the planning phase, he was able to check that the maximum amount of information was transferred; however after he and other key personnel left, the project suffered setbacks. This indicates the necessity to accumulate and consolidate both the technical and policy capabilities within organizations, rather than persons, so that the fact that people move on increases technology diffusion rather than stops projects.

Turnover of personnel is not necessarily a negative phenomenon. It can be an important mechanism to ensure technology diffusion, the training of new people and thus the consolidation of the technology developed within the country. But for these goals to be realized specific policy mechanisms need to be adopted which throughout the project should entail the frequent writing of technical reports, the compilation of research procedure manuals, internal training programmes and the communication of information to all interested groups.

Finally, any policy for the development of a bacterial leaching project should be alert to the possible social consequences of its application. Policy should be devised for the identification of any likely detrimental effects. If these are envisaged they should be resolved in collaboration with the people concerned.

The analysis of the Tasna and Pailaviri projects in Bolivia indicate that it is essential to carry out a preliminary evaluation of existing patterns of resource use. In Bolivia there are women miners working dumps for minerals (since they are not paid compensation for their husbands' deaths from mining accidents and diseases) at a much lower wage than male workers and without the social benefits to which the men are entitled; and family operators recuperating tin from mine water and streams, emanating from the mines or into which tailings have been dumped, which is then sold back to the firm. These activities are deeply interwoven within the mining economy of that country so that a cheap informal labour force seems to be inhibiting the necessity for major technical change and investment in modernization. COMIBOL has not opened a new mine since its establishment over thirty years ago; most of its plant and equipment date back beyond then and only about 57 per cent of the tin which is mined is recovered at the plant site due to obsolete plant and equipment.

This complex area requires much more study before any policy suggestions can be made. However it emerged clearly from the research that these groups of people, who are well organized at each mine site, should be involved in any decision making relating to the utilization of these resources. In the case of the women miners the work is highly dangerous, since the dumps are unconsolidated, and the 30 cents or so they receive daily, in contrast to the daily dollar rate received by male miners, is no substitute for the compensation they should be paid and social benefits they should be afforded.

Any policy response should therefore include the payment of adequate compensation and the creation of more humane and better paid work alternatives through, for example, planned mine expansion programmes.* Indeed an overall policy requirement, which relates to people, emerging from this research is the necessity to open up decision making processes. If a multidisciplinary team is to work together with researchers in close contact with production personnel there needs to be a full participation by these people in project planning and related decision making. Co-operation at the trade-union level would therefore be necessary. Frequent team meetings and the obligatory communication of information to both interested and affected groups is thus essential.

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* For example, planned mine expansion programmes which would incorporate these "informal" workers into the formally employed labour force entitling them to stable (albeit low) wages and some (albeit presently inadequate) social benefits.

## 2.3 Conclusion and some recommendations for further work

Emerging environmental and economic trends are combining to create a new technological context within which new mineral projects will be developed and existing ones will have to adapt to remain viable. This is having the effect of increasing the complexity and number of possible process routes available for mining and metal recovery. Furthermore, with the increasing necessity to recover by-products, pollutant elements and marginal ore, these process routes will be more closely determined by the geological specificities of each mine site.

As a consequence of this, and in the light of foreseeable advances in biotechnology, it is argued that bacterial leaching can contribute to broaden this range of process routes. Bacterial leaching can be applied not only to the traditional dump system but also to optimally designed heaps of marginal ore and concentrates as well as a series of previously unresolved problems in sulphide metallurgy.

The linking of biotechnology, mining and metallurgy imposes a new set of demands on the minerals industry. For example, multidisciplinary teams and closer links between research and production are required both at a national level and within the firm. There is also a need for wider decision making processes and a consideration of the environmental and social context of the technology's application; while, the nature of international technology transfer in this field is determined by the fact that virtually all commercial bacterial leaching operations in the developing countries are suboptimal dump systems and most of the related microbiological research is concentrated in institutes or universities.

As an alternative, or more exactly as an additional process route, the development and application of bacterial leaching technology in developing countries would therefore seem to pose challenges in two interrelated areas:

(i) Maximizing the benefits of international technology transfer both from developed countries and between developing countries;

(ii) Technology assimilation, adaptation and generation.

Given the context in which new mineral projects will be developed, and accepting that bacterial leaching will not be appropriate in every case, it is concluded that there are important benefits to be gained by the developing countries in rising to meet this challenge.

Firstly, the application of this technology enables the recuperation of normally unrecovered mineral values at relatively low marginal cost, the solution of certain metallurgical problems and the reduction of natural pollution.

Secondly, it is possible to identify a tendency inherent within the development of efficient bacterial leaching technology which leads to the localization of related technical change processes. This is because of the intrinsic necessity for local capability accumulation and utilization if the natural leaching process is to be optimized. Two principal reasons for this emerged from the research; they are:

(i) The essential input which site-specific mining, mineralogical metallurgical and geographical knowledge forms during the design, implementation and optimization of bacterial leaching projects;

(ii) The unreliability and impracticability of trying to develop parameters to optimize the environment-sensitive activity of the leaching bacteria outside of the production sector and away from the intended site of application.

The undertaking of such projects thus enhances control over technical change through a more substantive local participation in the process and, if the capabilities are consolidated, provides a dynamic for both technology diffusion processes and the application of the capacity to other areas of technology development in the minerals industry. Furthermore, the ongoing requirements involved in optimizing bacterial leaching operations similarly stimulate the accumulation of indigenous capabilities to effect incremental technical change which again leads to increased local participation in mineral production.

In the case of bacterial leaching technology development in the Andean region this was manifested in the clear trend for firms and institutes to reorganize themselves in order to efficiently develop and implement bacterial leaching projects. This involved the translation of the technical change activities, in some cases in spite of the policy, not just to the industrial sector but also closer to the production division within the firm.

However, it cannot be overemphasized that the precise biochemical mechanisms at work and the detailed characteristics, including the genetics of the leaching bacteria themselves are still inadequately understood. This means the potential for optimization still has to be realized. Furthermore, there is a corresponding lack of knowledge about the full nature and extent of mineral reserves to which the process can be applied. As a consequence, at this stage, it is impossible to determine with accuracy the economic impact that bacterial leaching may have on the minerals sector of developing countries.

In the light of this, some recommendations are made which identify general areas where work is required to complement the project policy outlined above, if the potential bacterial leaching offers to the mineral-producing developing countries is to be reliably assessed.*

(a) Inventories could be compiled of existing dumps which include their mineral contents and microbiological characteristics. This would require a programme of systematic geological evaluation and microbiological field-work. A survey of existing patterns of resource use (i.e. mine water and dumps) could complement this. The specific needs of developing countries in this area can be defined and research programmes designed and implemented in co-operation with industry;

(b) Existing genetic engineering research programmes could be explored to determine the necessary mechanisms required to expand them to include work on leaching bacteria;

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* The recommendations are of a general nature. In section 1.4.3, a list is presented of specific technical areas which require more research.

(c) Research could be carried out in the developing countries to establish the potential bacterial leaching offers for the resolution of other metallurgical problems like gold-bearing pyrite ores and arsenic-contaminated copper concentrates. Technology development projects at either a national or regional level could be planned accordingly;

(d) Given that the technology required to optimize bacterial leaching processes is largely disembodied, an international information system could be set up to aid technology search in this area. This could list experts, research centres and industrial bacterial leaching operations, and make available details concerning expertise, experience and conditions for technology transfer. It could include staff to investigate the international state of the art of technology development in bacterial leaching and to compile and update related literature from both the academic and industrial press. Such a centre could also help to set up and co-ordinate consultancy work to be undertaken by already specialized groups in bacterial leaching in the developed and developing countries;

(e) Funds could be provided for international workshops to train developing-country researchers and engineers. Grants could be provided for training or research fellowships at universities and institutes specializing in bacterial leaching. A fund could be established to enable developing country experts in bacterial leaching to attend the increasing number of international conferences in this field. Visiting experts could be funded in such a way as to obtain economies of scale through the undertaking of regional consultancies rather than visits to one country only;

(f) An inventory could be compiled of existing small-scale operations. These could be assessed to discover whether there exists a microbiological component (i.e. through microbiological analyses of the leach solution and local mine water); and, if there does, mechanisms could be devised to communicate to operators (who may not read) how optimization can be achieved;

(g) International meetings could be held to inform national mining companies and research institutes of the potential of bacterial leaching and the advantages of undertaking both geological surveys of their dumps and marginal ore and anticipative research on the leachability of local ores. This could include all countries presently producing from, or planning to develop sulphide mineral deposits. These meetings may be held best at a subregional level so that mining companies and research institutes working in similar mineral zones can be brought together.

Overall it is concluded that the potential for applying biotechnology to the minerals industry of developing countries is both promising and positive. However, if the benefits offered by optimized bacterial leaching projects are to be harnessed to contribute to the development of the minerals sectors of developing countries there emerges a clear necessity for a technology policy approach.

It is hoped that this paper helps in some way to provide useful suggestions and ideas for the components of such a technology policy.

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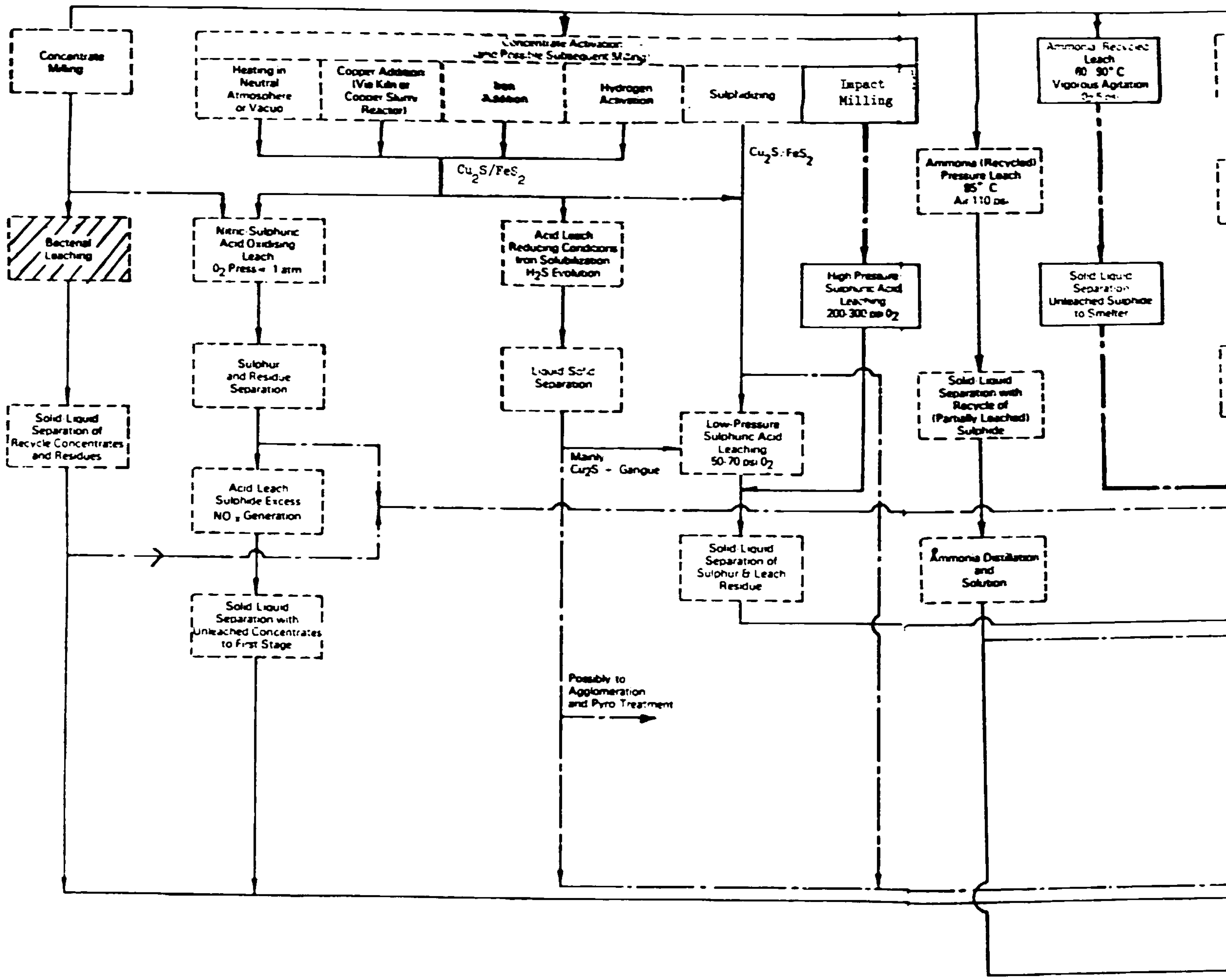
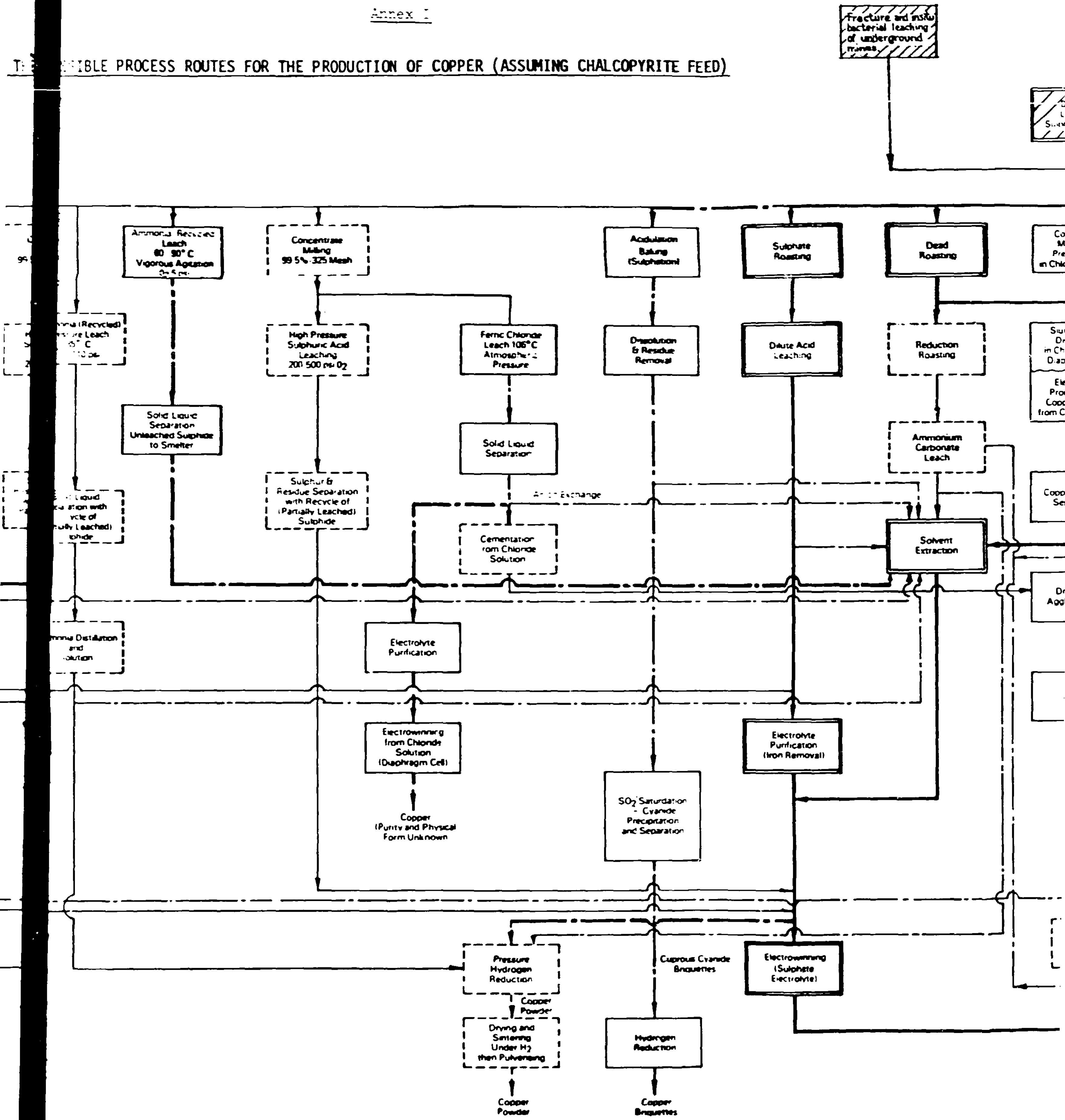
POSSIBLE PROCESS ROUTES FOR



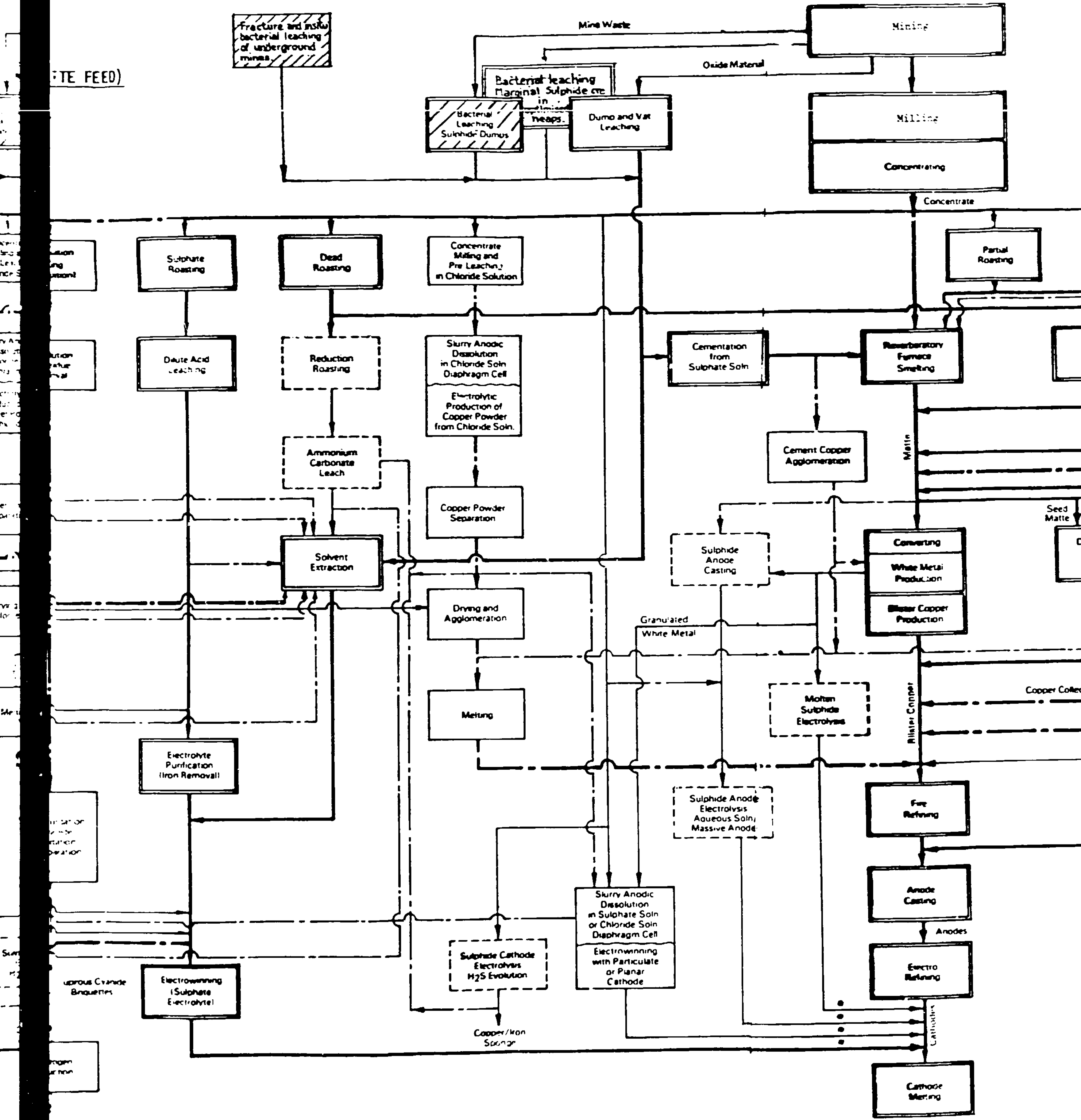

SECTION 1

Annex I

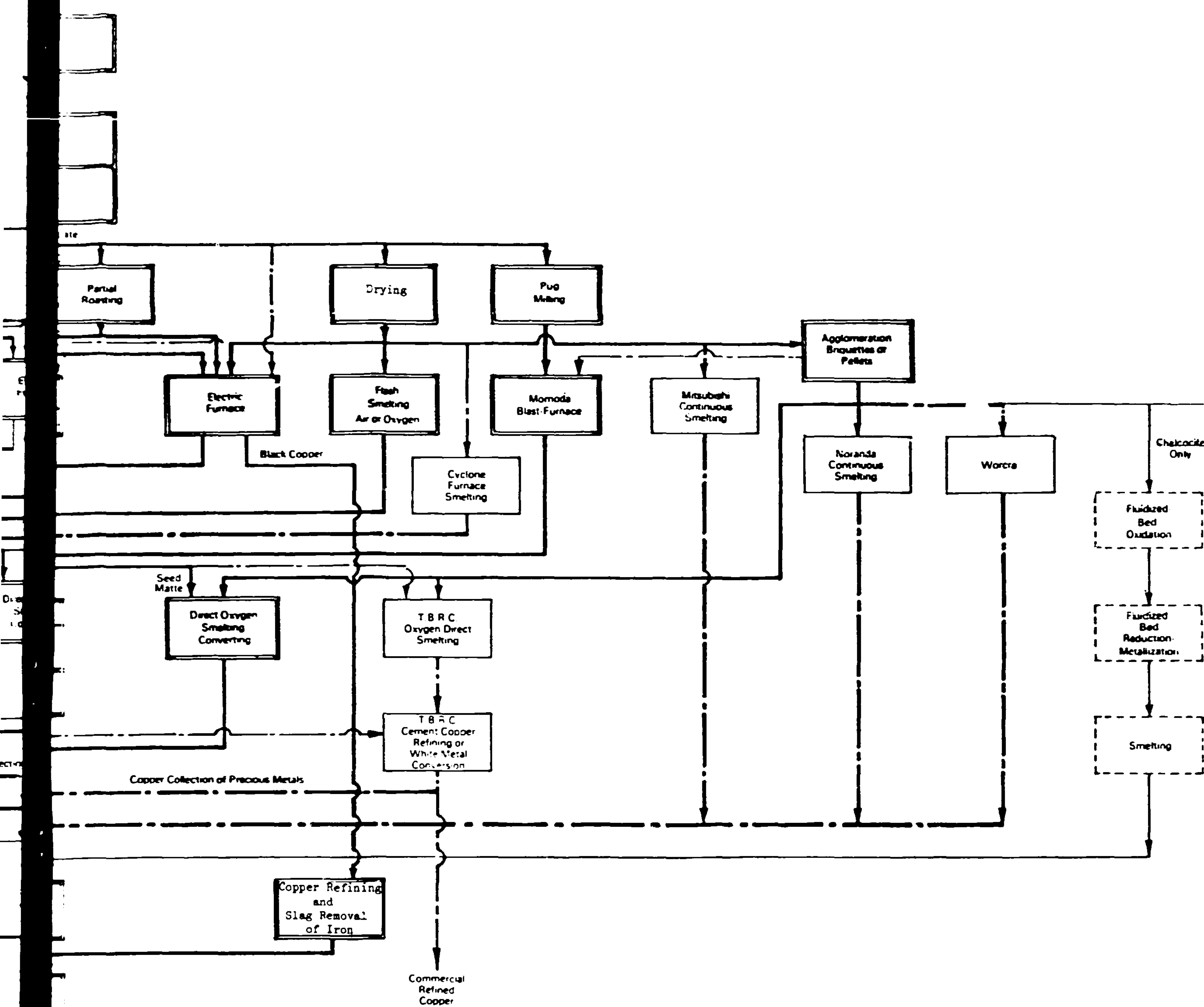
T[illegible]IBLE PROCESS ROUTES FOR THE PRODUCTION OF COPPER (ASSUMING CHALCOPYRITE FEED)

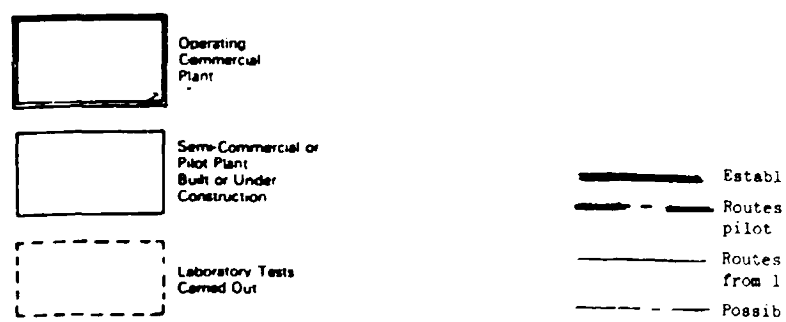



SECTION 2


TE FEED)
Fracture and insitu bacterial leaching of underground mines
Mine Waste
Mining
Oxide Material
Bacterial leaching Marginal Sulphide ore in heaps.
Bacterial Leaching Sulphide Dumps
Dump and Vat Leaching
Milling
Concentrating
Concentrate
Sulphate Roasting
Dead Roasting
Concentrate Milling and Pre Leaching in Chloride Solution
Partial Roasting
Dilute Acid Leaching
Reduction Roasting
Slurry Anodic Dissolution in Chloride Soln Diaphragm Cell
Electrolytic Production of Copper Powder from Chloride Soln.
Cementation from Sulphate Soln
Reverberatory Furnace Smelting
Ammonium Carbonate Leach
Cement Copper Agglomeration
Matte
Copper Powder Separation
Seed Matte
Solvent Extraction
Sulphide Anode Casting
Converting
White Metal Production
Blister Copper Production
Drying and Agglomeration
Granulated White Metal
Melting
Molten Sulphide Electrolysis
Blister Copper
Copper Collec
Electrolyte Purification (Iron Removal)
Sulphide Anode Electrolysis Aqueous Soln; Massive Anode
Fire Refining
Anode Casting
Anodes
Slurry Anodic Dissolution in Sulphate Soln or Chloride Soln Diaphragm Cell
Electrowinning with Particulate or Planar Cathode
Sulphide Cathode Electrolysis H2S Evolution
Electrowinning (Sulphate Electrolyte)
Cuprous Cyanide Briquettes
Electro Refining
Cathodes
Copper/Iron Sponge
Cathode Melting

# SECTION 3



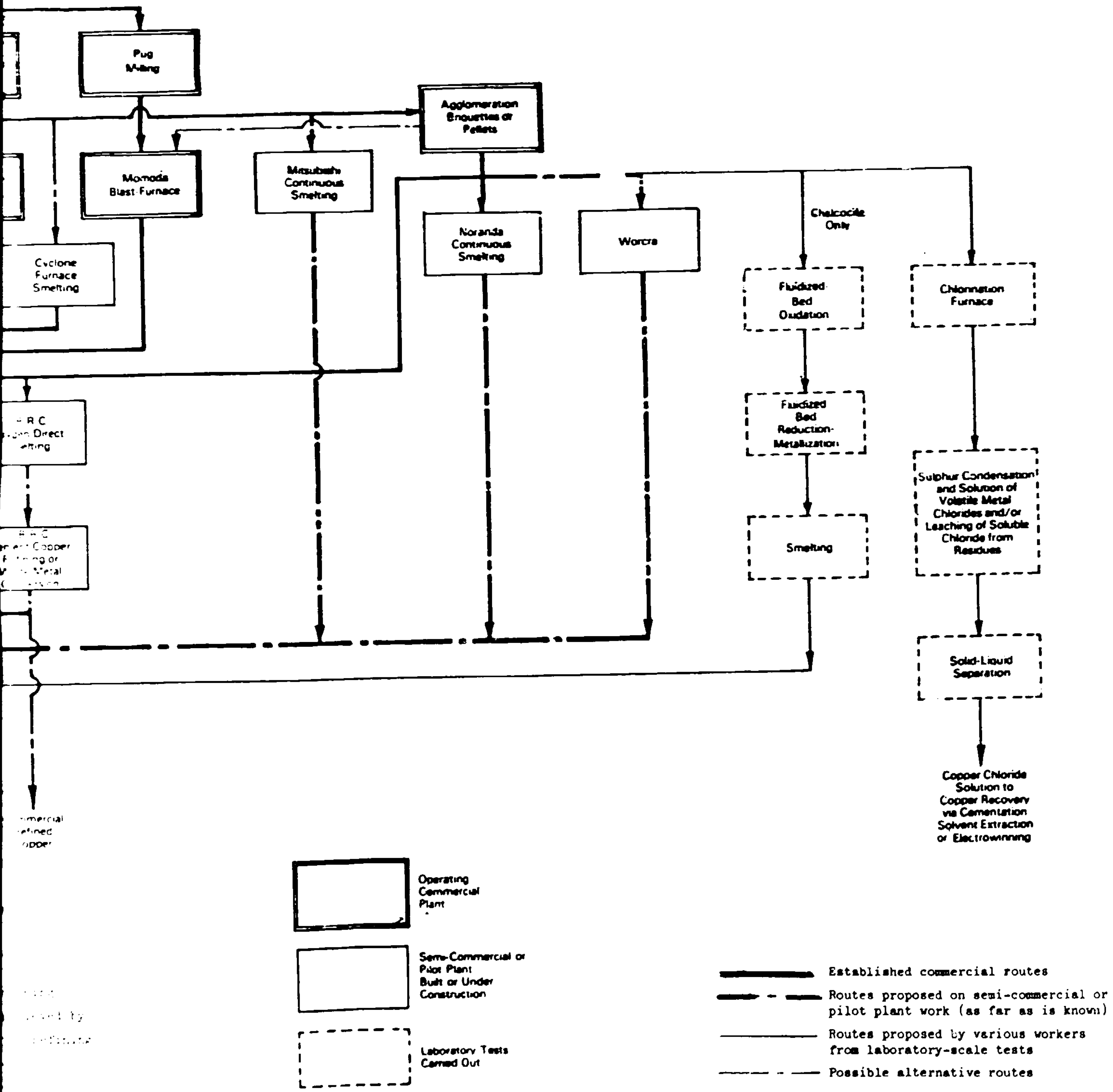




● NOTE:

There may be difficulty in obtaining Cathode Purity equal to that achieved by commercially established Electro Refining

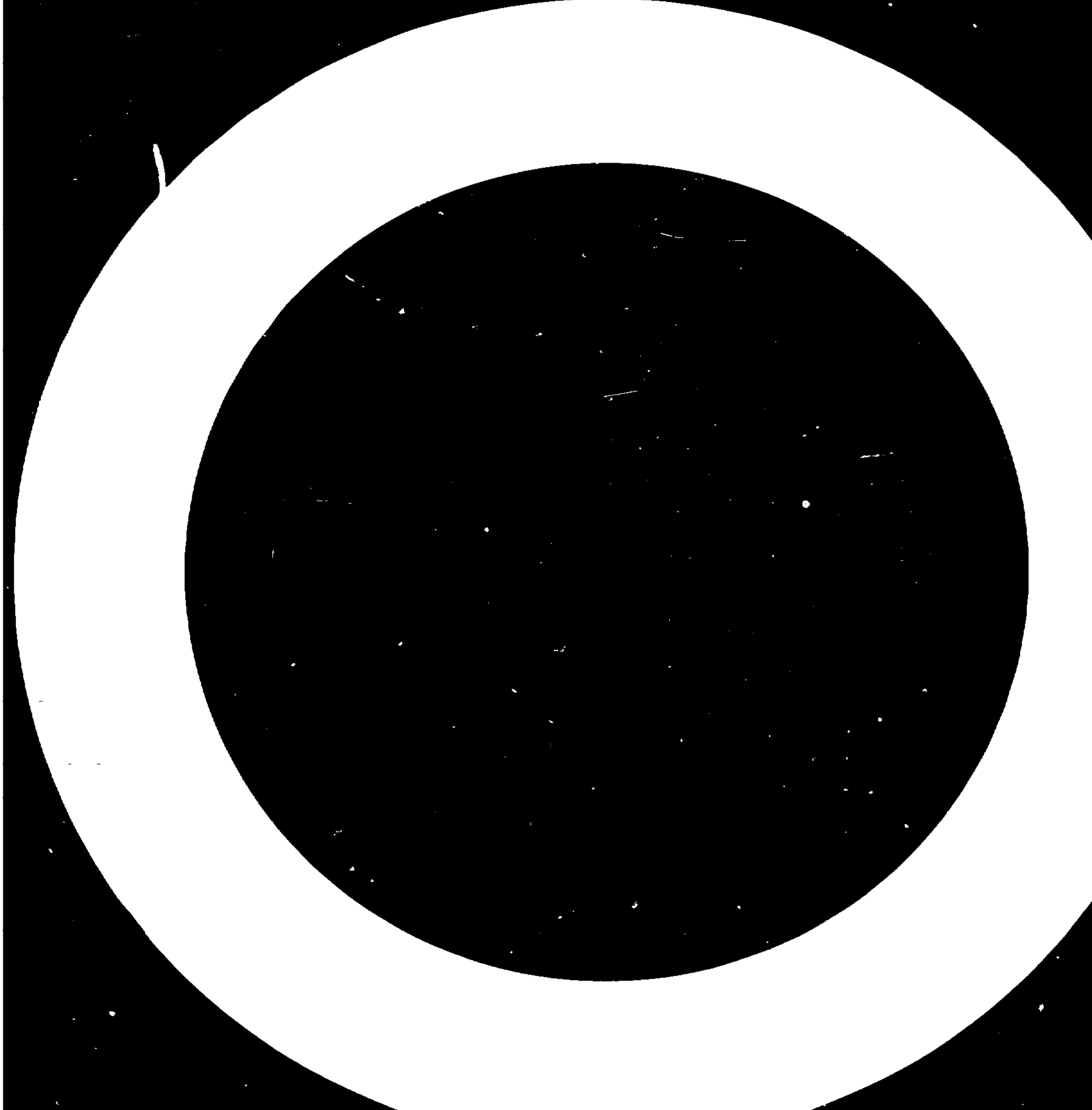
SECTION 4

Source: Adapted from M. J. Cahalan, C. E. Woods and J. F. Castle, "Some aspects of the changing technology of extraction of copper from sulphides", Minerals an[d] the Environment, Paper [illegible], June 1974.




Source: Adapted from M. J. Cahalan, C. E. Woods and J. F. Castle, "Some aspects of the changing technology of extraction of copper from sulphides", Minerals and the Environment, Paper [illegible], June 1974.

SECTION 5



## SUMMARY OF OPERATING DATA FOR SOME MAJOR COMMERCIAL BA

| Mine location and/or company | Type of operation | Mineralization: Primary sulphides or oxides | Mineralization: Total Cu (%) | Mineralization: Host rock | Mean total weight of rock being leached (kg) | Waste (ore) body height/width | Irrigation rate and mode (influent flow rate, l/min.)[c] | Area irrigated ($m^2$) | Starting solution (influent) (g/L): Cu | $Fe^{2+}$ | $Fe^{3+}$ | pH | Tot. Efflu. flow r (ℓ/m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Old Reliable, Mammoth, Arizona, U.S.A. Ranchers Exploration and Development | In-Situ | 70% Sulphides ($Cu_2S$, $CuFeS_2$) 30% Oxides (chrysocholla) | 0,8 | Andesite | $4 \times 10^9$ | 103 m/106 m | 4,158 (1.100 gal./min.) continuous | 4,600 | 0,06 | 4,30 | 0,30 | 1,8 | 4,15 (1,100 gal |
| Bluebird Mine Miami, Arizona, U.S.A. Ranchers Exploration and Development | Heap | 100% Oxides chrysocholla | 0,5 | Schist | $4 \times 10^{10}$ | 61 m/183 m | 8,505 (2,300 gal./min.) intermittent | 92,000 | 0,20 | 0,03 | 0,63 | 6 g/ℓ $H_2SO_4$ | 8,70 (2,300 gal |
| Phelps Dodge Corp., Tyrone, New Mexico, U.S.A. | Dump | Pyrite, covellite, chrysocholla, tenorite chalcocite, chalcanthite | 0,35 | Quartz Monzonite | $3,9 \times 10^{10}$ | 71 m/792 m | 12,490 (330 gal./min.) intermittent, (2 cycles/yr.) | – | 0,30 | 1,52 | 1,20 | 3,8 | 12,1 (3,200 gal |
| Baghdad, Arizona, U.S.A. | Dump | Mixed oxides | 0,30 | – | – | – | 12,600 (3,328 gal./min.) continuous | – | 0,2 | 4,5 | 0,2 | 2,0 | 12,1 (3,200 gal |
| Duval Esperanza Mine, Arizona, U.S.A. | Dump | Chalcocite, malachite, azurite, chalcopyrite | 0,15–0,20 | Quartz monzonite and diorite | $2,7 \times 10^{10}$ | 91 m/366 m | 8,516 (2,250 gal./min.) continuous | – | 0.12 | 3,3 | 0,10 | 1,3 | 6,05 (1,600 gal |
| Duval, Mineral Park, Arizona, U.S.A | Dump | Chalcocite | 0,14 | Monzonite | $64 \times 10^{10}$ | 152 m/91 m | 7,570 (2,000 gal./min.) intermittent, periodic rest cycles | 457,640 | 0,05 | 2,85 | <0.01 | 3,8 | 6,81 (1,800 gal |
| Duval, Copper Basin, Arizona, U.S.A. | Dump | 85% sulphide | 0,31 | Sandstone; siltstone | $3,9 \times 10^{10}$ | 46m/366 m | 5,678 (1,500 gal./min.) intermittent, periodic rotation | 74 000 | 0,08 | 2,50 | 2,50 | 1,7 | 4,16 (1,100 gal |
| Duval, Copper Canyon, Arizona, U.S.A. | Dump | Oxide | 0,25 | Sandstone, porphyry | $3,9 \times 10^{10}$ | 122m/349 m | 4,542 (1,200 gal./min.) intermittent, periodic rotation | 74,000 | 0,02 | 1,2 | 0,10 | 1,9 | 3,78 (1,000 gal |
| Degtyansky, Urals USSR | Dump and in-Situ | Chalcopyrite, chalcocite, pyrite | – | – | – | – | – | – | 0,1 | 0,2 | 2,0 | 2,5-2,9 | – |
| Rio Tinto, Spain | Dump | Chalcocite, chalcopyrite, pyrite | variable | – | – | – | – | – | 0,2 | 4,0 | 1,0 | 1 g/ℓ $H_2SO_4$ | – |
| Cananea, Mexico | Dump and In-Situ | Chalcocite, pyrite | variable 025,35 | – | – | – | – | – | 0,35 | 7,1 | 1,8 | 2,7 | – |
| Kosaka Mine, Kosaka Town, Akita Prefecture, Japan | In-Situ (Monto-yama) | Silicified pyrite ores; chalcopyrite, chalcocite, bornite | 0,15–0,25 | – | $4,5 \times 10^9$ | – | 4,600 (1,215 gal./min.) sprinkled at 4-5 mo. intervals | – | 0,14 | 2,7 | 0,3 | 1,8 | 4,14 (1,090 gal |

SOURCE: L.E. Murr, "Theory and Practice of Copper Sulphide Leaching in Dumps and in-situ", in Minerals Science and Engineering, Vol. 12, No. 3, July, 1980.

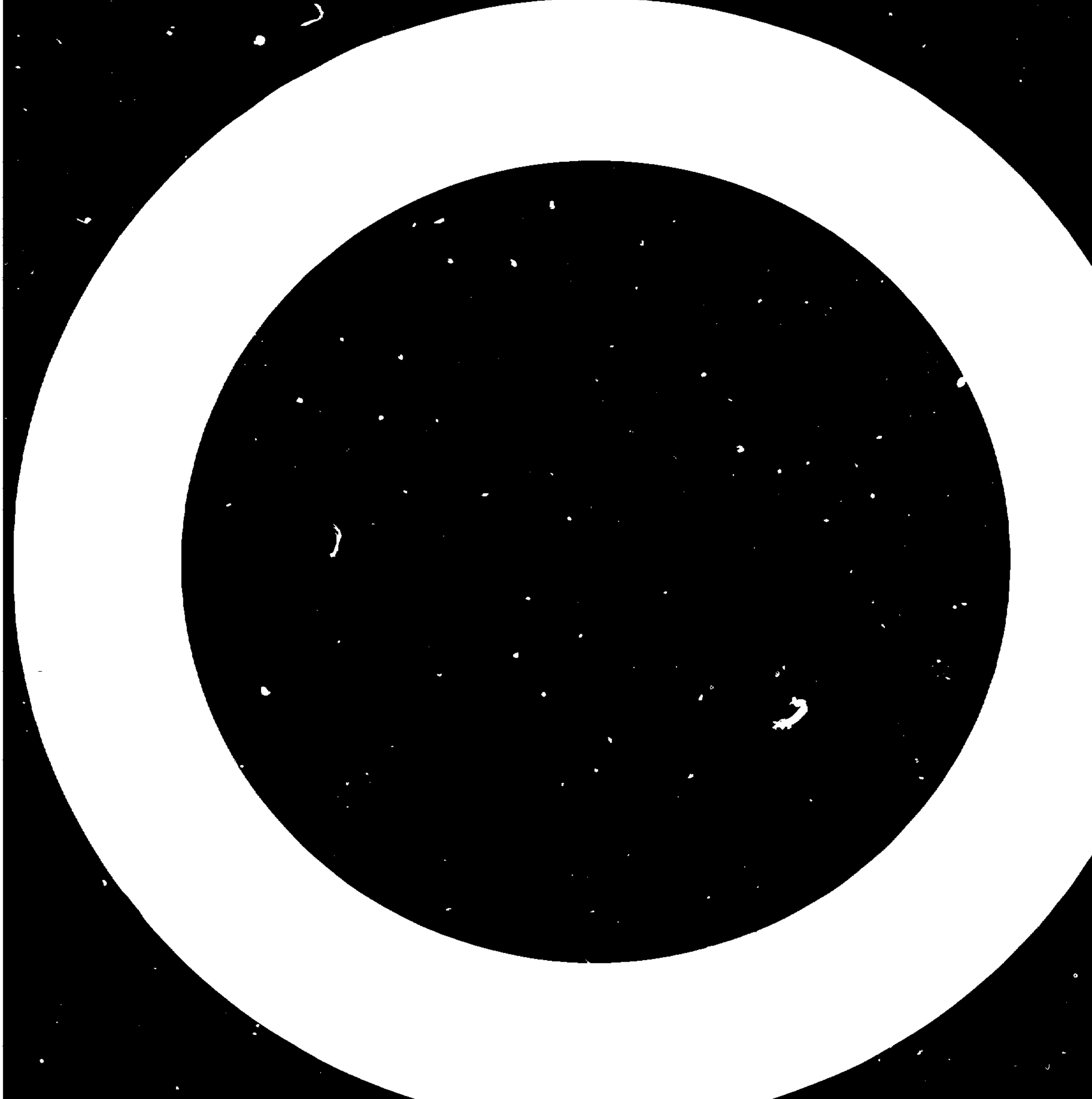
# SECTION 1

Annex II

## R SOME MAJOR COMMERCIAL BACTERIAL LEACHING OPERATIONS

| Area rigated m²) | Starting solution (influent) (g/L) | | | | Total Effluent flow rate (ℓ/min.) | Finishing solution (effluent) (g/L) | | | | Bacteria detected in solution effluent | Maximum/minimum waste (ore) body temperature | Recovery method | Average annual copper production (kg) | Years of operation | Estimated percent Cu recovered (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cu | $Fe^{2+}$ | $Fe^{3+}$ | pH | | Cu | $Fe^{2+}$ | $Fe^{3+}$ | pH | | | | | | |
| 4,600 | 0,06 | 4,30 | 0,30 | 1,8 | 4,158 (1,100 gal./min.) | 0,55 | 2,20 | 1,40 | 2,2 | unknown | 30°C/22°C | Cementation on iron scrap | 1 x $10^6$ | 3 | 18 |
| 92,000 | 0,20 | 0,03 | 0,63 | 6 g/ℓ $H_2SO_4$ | 8,705 (2,300 gal./min.) | 1,80 | 0,03 | 0,63 | 3 g/ℓ | unknown | unknown | Solvent extraction | 6,8 x $10^6$ | 16 | 40 |
| – | 0,30 | 1,52 | 1,20 | 3,8 | 12,112 (3,200 gal./min.) | 0,78 | 4,10 | 0,10 | 2,5 | *T. ferrooxidans* | 30°C/19°C | Cementation on iron scrap | 4,5 x $10^6$ | 9 | 25 |
| – | 0,2 | 4,5 | 0,2 | 2,0 | 12,100 (3,200 gal./min.) | 1,0 | 0,1 | 3,0 | 2,5 | *T. ferrooxidans* | unknown | – | 13,6 x $10^6$ | – | – |
| – | 0.12 | 3,3 | 0,10 | 1,3 | 6,056 (1,600 gal./min.) | 0,90 | 0,30 | 1,60 | 2,0 | *T. ferrooxidans* | effluent temp. | Cementation on iron scrap | 2,5 x $10^6$ | 15 | 30 |
| 457,640 | 0,05 | 2,85 | <0.01 | 3,8 | 6,813 (1,800 gal./min.) | 0,55 | 0,25 | 0,95 | 2,5 | *T. ferrooxidans* | 25°C maximum | Cementation on iron scrap | 1,5 x $10^6$ | 14 | 40 |
| 74 000 | 0,08 | 2,50 | 2,50 | 1,7 | 4,164 (1,100 gal./min.) | 1,1 | 2,5 | 2,5 | 2,2 | unknown | effluent temp. 24-32°C | Solvent extraction in 1980, cementation prior to 1980 | 2,3 x $10^6$ | 13 | 40 |
| 74,000 | 0,02 | 1,2 | 0,10 | 1,9 | 3,785 (1,000 gal./min.) | 0,90 | 0,02 | 0,20 | 2,9 | – | effluent temp. 7-15°C | Cementation on iron scrap | 1,7 x $10^6$ | 13 | 25 |
| – | 0,1 | 0,2 | 2,0 | 2,5-2,9 | – | 0,3 | 1,5 | 0,7 | 2,9 | *T. ferrooxidans* | – | Cementation on iron scrap | ~ 9 x $10^5$ | ~ 20 | – |
| – | 0,2 | 4,0 | 1,0 | 1 g/ℓ $H_2SO_4$ | – | 2,2 | 18 | 2 | 11 g/ℓ $H_2SO_4$ | *T. ferrooxidans* | unknown | Cementation on iron scrap | 8 x $10^6$ | hundreds | unknown |
| – | 0,35 | 7,1 | 1,8 | 2,7 | – | 3,3 | 3,0 | 7,4 | 2,3 | *T. ferrooxidans* | unknown | Cementation on iron scrap | 8,7 x $10^6$ | – | – |
| – | 0,14 | 2,7 | 0,8 | 1,8 | 4,140 (1,090 gal./min.) | 0,44 | 2,4 | 0,9 | 1,8 | $10^6$ cells/mℓ *T. ferrooxidans* | 24°C/17°C | Cementation on iron scrap | ~ 8 x $10^5$ | ~ 30 | unknown |

# SECTION 2



## Annex III

## SOME CHARACTERISTICS OF THE MINERALS SECTOR OF BOLIVIA AND PERU

Tables



************

### Introductory Note

Details of the relative importance of copper to Bolivia and Peru in terms of production, value of exports and reserves and some characteristics of their mineral industries are summarized here in annex III.

Peru has long established large-scale and open pit commercially viable copper operations and more recent smelter and refinery complexes. In 1979, it had an estimated 32 million metric tons of known copper reserves (which place it fifth in the world) and 103 million metric tons of probable reserves. In 1981, Peru produced 327,600 metric tons of copper and several new large-scale mineral projects are being planned. Peru is also an important world producer of iron ore, lead, zinc, antimony, silver, molybdenum and gold.

Bolivia, on the other hand, has a very small-scale copper industry. Unlike Peru's large sulphide porphyry deposits the developed mines are small massive sulphide bodies with oxidized upper layers. These are mined by underground methods. Bolivia has experienced little technology development at the processing stage and after a crude flotation process concentrates are sold directly to Japan. In 1981, Bolivia produced a total of only 2,637 metric tons of copper. Bolivia, however, is an important world producer of tin, lead, zinc, wolfram, silver and gold. Although, it is important to note that only 10 per cent of the mineralized zone of Bolivia has been explored geologically and COMIBOL has not opened any new mines since it took over most of the country's mining activites (80 per cent) in 1952.

The different technical bases of each country and indeed of each company and mine are important in explaining the lack of co-operative participation throughout the Copper Project's development.

ANNEX III

TABLE 1.

BOLIVIA: PRODUCTION OF PRINCIPAL MINERALS, 1970-1981

(in thousand tons)

| MINERALS | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tin (concentrate) | 29.4 | 23.5 | 23.8 | 31.2 | 30.2 | 32.0 | 30.3 | 33.7 | 30.9 | 27.8 | 27.3 | 29.8 |
| Antimony | 11.6 | 11.7 | 13.1 | 15.8 | 14.9 | 16.1 | 17.0 | 16.1 | 12.7 | 13.0 | 15.5 | 15.3 |
| Wolfram | 2.4 | 2.6 | 2.7 | 2.6 | 2.5 | 2.3 | 3.2 | 3.0 | 3.2 | 3.1 | 3.4 | 3.5 |
| Zinc | 46.5 | 45.4 | 39.7 | 53.4 | 49.4 | 48.8 | 53.0 | 63.5 | 59.3 | 44.1 | 50.3 | 44.0 |
| Copper | 9.0 | 7.8 | 8.4 | 8.9 | 7.2 | 6.2 | 5.1 | 3.1 | 3.3 | 1.8 | 1.9 | 2.6 |
| Lead | 25.8 | 23.3 | 19.0 | 24.2 | 19.5 | 18.0 | 19.2 | 18.9 | 18.0 | 15.4 | 17.2 | 16.8 |
| Bismuth | 0.6 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.4 | 50.0 | 50.0 | 11.0 |
| Silver | 185.6 | 172.4 | 143.2 | 171.3 | 155.2 | 160.1 | 169.2 | 180.8 | 200.3 | 178.6 | 189.7 | -- |
| Gold (fine kg) | 862.1 | 655.3 | 674.5 | 1,151.6 | 1,307.0 | 1,648.8 | 1,292,0 | 755.1 | 1,088.2 | 948.0 | 1,619.7 | -- |

Source: Based on data collected by Statistics Division, Andean Pact.

ANNEX III

TABLE 2

PERU: PRODUCTION OF PRINCIPAL MINERALS, 1970-1981
(thousand tons)

| MINERALS | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Copper | 218 | 213 | 226 | 215 | 222 | 176 | 224 | 338 | 366 | 392 | 361 | 327 |
| Iron | 6,249 | 5,617 | 6,086 | 5,852 | 6,220 | 5,067 | 3,089 | 4,173 | 3,328 | 4,955 | 5,754 | 4,038 |
| Silver (fine tons) | 1,217 | 1,264 | 1,269 | 1,287 | 1,215 | 1,201 | 1,228 | 1,235 | 1,151 | 1,220 | 1,337 | --- |
| Zinc | 360 | 386 | 448 | 459 | 450 | 433 | 457 | 405 | 402 | 432 | 477 | 496 |
| Lead | 164 | 172 | 190 | 198 | 179 | 168 | 173 | 170 | 170 | 174 | 184 | 187 |
| Gold | 2,954 | 2,725 | 2,728 | 3,137 | 3,350 | 3,368 | 2,296 | 3,247 | 3,504 | 4,155 | 3,923 | --- |

Source: Based on data collected by Statistics Division, Andean Pact.

ANNEX III

TABLE 3

BOLIVIA: VALUE OF PRINCIPAL MINERAL EXPORTS, 1970-1981

(in millons of dollars and as a percentage of all exports)

| | 1970 | | 1975 | | 1978 | | 1979 | | 1980 | | 1981 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VALUE | % | VALUE | % | VALUE | % | VALUE | % | VALUE | % | VALUE | % |
| All minerals | 204 | 90 | 312 | 59 | 520 | 71 | 584 | 70 | 640 | 61 | 554 | 56 |
| Tin concentrate | 107 | 47 | 130 | 25 | 173 | 24 | 167 | 20 | 140 | 13 | 77 | 8 |
| Metallic tin | - | -- | 51 | 10 | 213 | 29 | 232 | 28 | 248 | 24 | 266 | 27 |
| Copper | 12 | 5 | 7 | 1 | 4 | -- | 3 | -- | 4 | -- | 4 | -- |
| Silver | 11 | 5 | 29 | 5 | 34 | 5 | 58 | 7 | 118 | 11 | 72 | 7 |
| Lead | 8 | 4 | 8 | 1 | 11 | 2 | 18 | 2 | 14 | 1 | 11 | 1 |
| Zinc | 14 | 6 | 40 | 8 | 31 | 4 | 43 | 5 | 37 | 4 | 40 | 4 |
| Others | 52 | 23 | 47 | 9 | 54 | 7 | 63 | 8 | 79 | 8 | 84 | 9 |
| TOTAL EXPORTS | 226 | 100 | 530 | 100 | 733 | 100 | 834 | 100 | 1,048 | 100 | 977 | 100 |

Source: Statistics Division, Andean Pact.

ANNEX III

TABLE 4

PERU: VALUE OF PRINCIPAL MINERAL EXPORTS, 1970 - 1981
(in millons of dollars and as percentage of all exports)

| | 1970 | | 1975 | | 1978 | | 1979 | | 1980 | | 1981 (Provisional) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VALUE | % | VALUE | % | VALUE | % | VALUE | % | VALUE | % | VALUE | % |
| All minerals | 505 | 48 | 568 | 43 | 834 | 46 | 1,529 | 45 | 1,404 | 42 | 1,559 | 48 |
| Copper | 278 | 27 | 165 | 13 | 390 | 21 | 689 | 20 | 624 | 19 | 529 | 16 |
| Iron | 67 | 6 | 55 | 4 | 69 | 4 | 86 | 3 | 80 | 2 | 93 | 3 |
| Silver | 29 | 3 | 83 | 6 | 102 | 6 | 223 | 7 | 76 | 2 | 312 | 10 |
| Gold | 3 | - | -- | - | 15 | 1 | 10 | - | 43 | 1 | N.D | -- |
| Zinc | 47 | 4 | 173 | 13 | 102 | 6 | 154 | 4 | 191 | 6 | 272 | 8 |
| Lead | 63 | 6 | 74 | 6 | 138 | 7 | 290 | 9 | 333 | 10 | 219 | 7 |
| Others | 18 | 2 | 18 | 1 | 18 | 1 | 77 | 2 | 57 | 2 | 134 | 4 |
| TOTAL EXPORTS | 1,048 | 100 | 1,315 | 100 | 1,820 | 100 | 3,390 | 100 | 3,309 | 100 | 3,255 | 100 |

Source: Statistics Division, Andean Pact.

ANNEX III

TABLE 5

BOLIVIA: NATURE OF MINERAL RESERVES, 1979

(tons of contained metal)

| MINERAL | KNOWN RESERVES | POTENTIAL RESERVES |
|---|---|---|
| Copper | 26,657.50 | 247,932.00 |
| Tin | 636,948.98 | 783,819.84 |
| Silver | 1,981.02 | 1,634.78 |
| Lead | 106,748.68 | 309,144.171 |
| Zinc | 1,007,688.62 | 627,676.00 |
| Antimony | 96,781.00 | 241,630.00 |
| Wolfram | 24,577.90 | 63,138.00 |
| Bismuth | 4,605.90 | 67,700.00 |
| Gold | 1,148.13 | ---- |
| Iron | --- | 20,014,300,000.00 |
| Manganese | --- | 10'000,000.00 |

Source: J.F. Royo, Reservas de Minerales en Bolivia (La Paz. SIC Ltd., 1981).

ANNEX III

TABLE 6

PERU: NATURE OF MINERAL RESERVES, 1979

(tons of contained metal)

| MINERAL | KNOWN RESERVES | POTENTIAL RESEFVES |
|---|---|---|
| Copper | 24,000,000 | 103,000,000 |
| Silver | 20,000 | 69,000 |
| Lead | 3,990,000 | 12,000,000 |
| Zinc | 11,220,000 | 25,000,000 |
| Iron | 316,500,000 | 3,130,000,000 |
| Minor Elements | 366,000 | --- |

Source: Orientación General del Plan Nacional de Desarrollo, 1982-1985, Instituto Nacional de Planificación, Lima, 1981.

# ANNEX IV

## SOURCE MATERIAL FOR THE ANDEAN PACT COPPER PROJECT

The Technology Policy Group of the Board of the Cartagena Agreement kindly facilitated many interviews with personnel in the state and private sector of the Bolivian and Peruvian mining industry and data collection at the mines mentioned in the text. They also made available a series of documents which proved to be fundamental to the technical and policy discussions of the present paper.

Those sources of information which are not confidential are listed below:

### Documents prepared by the Andean Pact Copper Project (PADT-COBRE) as listed by the Technology Policy Group of the Board of the Cartagena Agreement (in chronological order)

Proyectos Andinos de Desarrollo Tecnológico en el área de la hidrometalurgia del cobre (J/GT/12), 2 September 1974.

Proyectos Andinos de Desarrollo Tecnológico en el área de la hidrometalurgia del cobre. Decisions 86 and 87 of the Board of the Cartagena Agreement (J/GT/ 16), 5 May 1975.

Equipamento para los Proyectos 1, 2 y 3 sobre hidrometalurgia del cobre (Appendix) (J/GT/16), 24 April 1975 and Rev.1, 12 June 1975.

Proyectos Andinos de Desarrollo Tecnológico en el área de la hidrometalurgia del cobre. Decisions 86 and 87 of the Board of the Cartagena Agreement (J/GT/16, Rev.1), 12 June 1975.

Potencial de la lixiviación bacteriana en el Perú. By William O Macha and César Sotillo Palomino (J/GT/19), 30 October 1975.

Proyecto III, "Intercambio iónico-electrodeposición" y "Conversatorio de intercambio iónico" prepared by the delegation of Peru. Decisión 87. Lima, September 1975 (J/GT/20), 18 December 1975.

Lixiviación bacteriana de minerales de cobre. By José Normand Guzmán (J/GT/21), 1 April 1976

Proyectos Andinos de Desarrollo Tecnológico en la hidrometalurgia del cobre, Decisión 87. Informe de la representación peruana. By W. O Macha, Alternative Representative and National Head of the Copper Project (J/GT/25), 2 June 1976.

Proyecto Andino de Desarrollo Technológico en el área de la hidrometalurgia del cobre. Proyecto II. Lixiviación bacteriana. Seminario. Prepared by the Delegation of Peru of Decision 87 and the Board of the Cartagena Agreement (J/GT/26), 10 June 1976.

PADT-Cobre. Decisión 87. Informe de la representación peruana al comité contratante. Lixiviación bacterial de minerales de cobre. Prepared by Alberto Herrera Banda; collaborators: Juan Fernández T., Aurelio Corimaya M., MINERO-PERU (J/GT/27/, 21 June 1976.

Informe de la representación peruana al comité contratante. Seminario Tarma. Mayo 1976. Lixiviación bacteriana, volumen X. Prepared by A. Corimaya, J. Fernández, A. Herrera, Central Laboratory, MINERO-PERU (J/GT/29), 8 September 1976.

Informe de la representación peruana al comité contratante. Seminario Tarma. Mayo 1976. Lixiviación bacteriana, volumen IX. Prepared by O. Delgado, C. Egoavil, Department of Metallurgical Research, CENTROMIN, Perú (J/GT/30), 8 September 1976.

Informe de la representación peruana al comité contratante (1° y 2° informe progresivo) Trabajos a escala de laboratorio y pruebas en columnas. By J. Zegarra and O. Delgado. Department of Metallurgical Research, La Oroya, CENTROMIN, Peru (J/GT/31), 22 September 1976.

Informe de la representación peruana al comité contratante. Mecanismos de reacción involucrados en la acción lixiviante de las bacterias (J/GT/32), 22 September 1976.

Informe de la representación peruana al comité contratante "Visitas a Plantas Hidrometalúrgicas de Chile" (J/GT/33), 27 September 1976.

PADT-Cobre Decisión 87. Informe de la representación peruana al comité contratante "Lixiviación bacteriana de minerales marginales de cobre–Toromocho" (Tercer Informe Progresivo) prepared by Juan Zegarra and Oscar Delgado, CENTROMIN, Peru (J/GT/34), 12 November 1976.

Informe de la representación peruana al comité contratante "Lixiviación bacteriana en columnas de mineral sulfurado de Cerro Verde" (J/GT/36), 30 January 1977.

PADT-Cobre. Decisión 87. Informe de la representación peruana al comité contratante "Avance de las pruebas de lixiviación química bacteriana en columnas y erlenmeyers", "Cultivos y adaptaciones de bacterias", "Pruebas de cementación e intercambio iónico" (J/GT/37), 30 January 1977.

PADT-Cobre. Decisión 87. Informe de la representación peruana al comité contratante "Lixiviación bacteriana en columnas de minerales marginales de Cerro Verde" (J/GT/38), 21 February 1977.

PADT-Cobre. Decisión 87. Informe de la representación peruana al comité contratante "Lixiviación bacteriana de minerales marginales de cobre–Toromocho" (J/GT/39), 21 February 1977.

PADT-Cobre. Decisión 87. Informe año 1976 del Jefe Nacional de Programa de Perú. Proyectos II y III (J/GT/40), 15 March 1977.

PADT-Cobre. Decision 87. Proyecto II. Informe de la representación peruana al comité contratante. "Seminario de electroquímica de semi-conductores y lixiviación bacteriana" (J/GT/41), 20 April 1977.

PADT-Cobre. Proyecto II. Decisión 87. Seminario teórico-práctico sobre electroquímica de semi-conductores y lixiviación bacteriana. Resumen corregido de la Conferencias (J/GT/43), 5 May 1977.

PADT-Cobre. Proyecto III. Decisión 87. Seminario de intercambio iónico. Comité contratante. Decisión 87 (J/GT/44), 17 May 1977.

PADT-Cobre. Decisión 87. Informe de la representación peruana, "Lixiviación bacteriana de minerales marginales de cobre-Toromocho" Escala Semi-piloto (J/GT/45), 10 August 1977.

PADT-Cobre. Decisión 87. Proyecto III. Informe del Jefe Nacional de Programa, Perú, sobre seminario de intercambio iónico-electrodeposición. Arequipa, 30 May-24 June 1977 (J/GT/46), 11 August 1977.

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In addition, the 'Final Acts' of the meetings of the contracting Committee, the administrative organ of the Andean Pact Copper Project, were an important source of information.

## GLOSSARY

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| Acid | Generally a substance, soluble in water, containing hydrogen which can be replaced by metallic ions and thereby forming metallic salts. |
| Acid mine water | Natural drainage water of mine sites which contains sulphuric acid and dissolved metallic salts (especially ferric ions) as a result of the biological and chemical breakdown of sulphuric minerals in rocks. |
| Acidophylic | An adjective used to describe bacteria which require a highly acidic environment for growth. |
| Autotrophic organisms | Capture carbon dioxide directly from the atmosphere and use the carbon for the synthesis of cellular components. |
| Beneficiation | Improving the chemical or physical properties of an ore so that metal can be recovered at a profit. Also known as mineral dressing. |
| Catalyst | A substance which enables a chemical reaction to occur or alters the rate at which a chemical reaction occurs, but is itself unchanged at the end of the reaction. |
| Chemolithtrophic | Obtains energy from oxidation of inorganic substances. |
| Chemosynthetic | An organism which utilizes the oxidation of inorganic autotroph compounds as the energy source for assimilation of carbon dioxide. |
| Cut-off grade | Minimum grade of ore which is considered economically viable to extract. This measure is employed to separate waste and marginal ore from concentrate feed; varies for each mine. |
| _Desulfovibrio_ | A genus of strictly anaerobic, mobile, rod-shaped bacteria in the family of _Spirillaceae_ which reduces sulphates to hydrogen sulphide. |
| Enzymes | Organic catalysts produced by living cells. |
| Gangue | Minerals found in association with ores (e.g. quartz) which are not themselves economically viable. If they consume acid (i.e. are calcareous) they may adversely affect bacterial leaching through consuming acid causing pH to rise. However, most porphyritic sulphide ores are found in a non-alkaline host rock (i.e. in association with non-acid consuming gangue). |

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| Heterotrophic organisms | Unable to capture carbon directly from the atmosphere and therefore forced to feed on the carbon of autotrophic organisms (i.e. dead or living). The vast majority of heterotrophic organisms feed on living or dead green plant. |
| Hydrometallurgy | Treatment of oxides, sulphides, mixed ores and concentrates through leaching whereby solutions dissolve minerals enabling the recovery of the contained metal from the "pregnant" solution. |
| Innovation | Employed in the text where the technical change process involves innovative components; that is, elements of new knowledge. These innovative components may be new for the firm or country and not necessarily the first applications in the world. |
| Jarosite | A hydrous sulphate of iron and potassium - a secondary mineral in ferruginous ores. |
| Lixiviate | To extract a soluble component from a solvent mixture by washing or percolation processes. |
| Matte | An impure metallic sulphide mixture produced by smelting the sulphide ores of such metals as copper, lead or nickel. |
| Mesophylic | An adjective used to describe bacteria which grow best at temperatures $20^{o}$-$45^{o}C$. |
| Ore or reserves | Mineral deposits where the metal-bearing minerals are sufficiently concentrated to be economically extracted given current production costs and metal prices. For copper, the arbitrary cut-off grade is presently less than 0.5 per cent metal contained in the metal-bearing mineral. |
| Oxidation | The addition of oxygen to a substance, or the removal of hydrogen from it. The term is generally used to refer to any reaction in which an atom loses electrons e.g. the transition of iron from the ferrous ($Fe^{++}$) to the ferric ($Fe^{+++}$) state or copper from the cuprous ($Cu^{++}$) to the cupric ($Cu^{+++}$) state. |
| Oxidizing agent | A substance or organisms capable of bringing about the chemical change known as oxidation. |
| pH | The concentration of hydrogen ions in a watery solution. |
| Plasmids | Structures in the cell cytoplasm which are able to reproduce autonomously. |

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| Porphyry sulphide deposits | Huge discontinuous belts of disseminated mineralization composed of iron sulphide (pyrite) and copper sulphide (e.g. chalcopyrite) minerals in association with lead, silver, molybdenum, arsenopyrite etc. depending on regional mineral zoning. |
| Potentiostat | An automatic laboratory instrument that controls the potential of a working electrode to within certain limits during coulometric (electrochemical reaction) titrations. |
| Pyrometallurgy | Treatment of sulphide ores, concentrates and metals in high temperatures. Includes processes of smelting and refining. |
| Resources | Marginal ore which may become economically viable in the near future. Arbitrary cut-off grade is 0.1 per cent copper content. |
| Solvent extraction | Metal recovery process in hydrometallurgy whereby dissolved metal ions in acid solutions (aqueous phase) are transferred to organic solutions to which reagent is added; aqueous and organic phases are then separated by mixer settler action and metal values stripped from the latter when concentrations are sufficiently high. |
| Substrate | A substance the reactivity of which is increased by a specific enzyme. |
| Sulphates | Salts of sulphuric acid. |
| Tailings | Waste product after preliminary mineral treatment (e.g. flotation); may contain sufficiently high mineral value to warrant reprocessing. |
| Technical change | Employed in the text in the general sense of any change made to the technical or organizational base of a production process. |
| Technological capabilities | Capabilities to effect specific technological capabilities activities, which are components of processes, which need direction and co-ordination before they can effect technical change. A capability framework to enable the various activities and tasks for a particular technical change process to be effectively carried out requires personnel (who will embody interrelated elements of knowledge, skill, and experience), techniques, facilities, equipment and funds which will operate in specific contexts and require co-ordination and direction. |
| Thermophylic | An adjective used to describe bacteria which need a temperature from 45$^{o}$-65$^{o}$C for their development. |