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COPPER DUMP LEACHING AND MANAGEMENT PRACTICES THAT MINIMIZE THE POTENTIAL FOR ENVIRONMENTAL RELEASES

by

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16. ABSTRACT

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Seepage from leach dumps and process solution collection systems is the most significant potential mechanism for the release on contaminants. These solutions have low pH and high concentrations of metals and total dissolved solids (TDS). Ground-water impacts have been documented. The application and efficiency of standard waste management practices at dump leach operations are site-specific and are limited by the magnitude of these facilities.

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FOREWARD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of the State and local governments, and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report presents a description of the magnitude and distribution of copper dump leaching, the design and operation of leaching facilities, the potential for environmental impact, and management practices that can be used to minimize environmental releases. The information contained in the report was obtained through searches of published and unpublished literature and through contact with knowledgeable individuals involved in the dump leaching industry. Ten leaching operations were visited to acquire firsthand knowledge and site-specific information. Seepage from leach dumps and process solution collection systems is the most significant potential mechanism for the release of contaminants. These solutions have low pH and high concentrations of metals and total dissolved solids (TDS). Ground-water impacts have been documented. The application and efficiency of standard waste management practices at dump leach operations are site specific and are limited by the magnitude of these facilities.

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SECTION 1

INTRODUCTION

BACKGROUND

The copper industry in the United States has been piling mine wastes (i.e., overburden and mine waste rock) and low-grade ores in and around mining sites for much of this century. Most of these wastes contain significant amounts of pyrites and other naturally occurring metal sulfides, but they contain too little copper for recovery by conventional milling. With the addition of sufficient water through precipitation, air, and the activity of autotrophic bacteria, this material can generate a leachate that has a low pH and contains high concentrations of copper and other metals.

In the 1920's, large-scale commercial leaching of these waste piles was initiated to recover the copper. These operations entailed the addition of sulfuric acid to the piles to accelerate the leaching process, collection of the leachate, and extraction of the copper by iron precipitation. The sites for these leach dumps were selected primarily to minimize haulage distances and thereby reduce costs. Very little consideration was given to how such sites would affect the environment. Consequently, most of the copper leaching operations were uncontrolled from an environmental standpoint, and at least some leachate entered the surface and ground waters surrounding the site.

Concerns about the environmental impact of mining operations began to gain public attention around 1970. Specific problems, such as discharges into surface waters and emissions into the air from copper recovery processes, were addressed by the Federal Water Pollution Control Act, the Clean Air Act, and various other Federal and State laws. The environmental effects of the solid waste management practices used by the mining industry at such sites, however, were not addressed until 1976, when the Resource Conservation and

Recovery Act (RCRA) was enacted. Section 8002(f) of RCRA required the U.S. Environmental Protection Agency (EPA) to conduct an investigation of all solid waste management practices in the mining industry. That mandate specifically directed EPA to conduct "a detailed and comprehensive study on the adverse effects of solid wastes from active and abandoned surface and underground mines on the environment, including, but not limited to, the effect of such wastes on humans, water, air, health, welfare, and natural resources."[1]

In 1980, Congress amended RCRA to exclude waste materials generated by the "extraction, beneficiation, and processing of ores and minerals" from many of the requirements of Subtitle C. The 1980 amendments also added Section 8002(p), which directed EPA to conduct a "detailed and comprehensive study on the adverse effects on human health and the environment, if any, of the disposal and utilization of solid wastes from the extraction, beneficiation, and processing of ores and minerals." In addition, Section 7 of these amendments (the "Bevill Amendment") amended Section 3001 to exclude these wastes from regulation under Subtitle C pending completion of the studies required by Sections 8002(f) and (p). The EPA was required to make a regulatory determination within 6 months after submitting the study to Congress as to whether regulations would be promulgated or if regulations were unwarranted for such mining and beneficiation wastes.[2]

A report mandated by Sections 8002(f) and (p) was submitted to Congress on December 31, 1985.[3] Copper dump leaching practices were among the extraction and beneficiation processes discussed in the report. The report treated copper leaching as a waste management system, which would make it subject to regulation under RCRA. The report concluded that the low pH and the potentially high concentrations of metals found in the leachates and leach material used in copper leaching operations made these wastes potentially hazardous to human health and the environment and possibly justify the listing of dump leaching wastes as hazardous.

On July 3, 1986, the EPA issued the regulatory determination required by Congress.[4] After reviewing the comments received in connection with its report to Congress, the EPA concluded that regulation of mining wastes under Subtitle C of RCRA was not warranted at this time. The notice indicated that RCRA's hazardous waste management standards "are likely to be environmentally unnecessary, technically infeasible, or economically impractical when applied to mining wastes." The EPA stated that "dump and heap leach piles are not wastes; rather, they are raw materials used in the production process. Similarly, the leach liquor that is captured and processed to recover metal values is a product, not a waste. Only the leach liquor which escapes from the production process and abandoned heap and dump leach piles are wastes." The EPA expressed continued concern, however, about problems associated with mining wastes, such as high acid-generation potential, radioactivity, asbestos content, and cyanide content. Because of these concerns, the EPA indicated that it would develop a program for mining wastes under Subtitle D of RCRA. This program will be designed to investigate and address the problems associated with mining wastes and will include criteria specifically tailored to the "unique characteristics" of mining operations.

To develop a program under Subtitle D that appropriately addresses the problems associated with mining wastes, the EPA must collect additional information on the nature of mining wastes, current waste management practices, and the potential for exposure to these wastes. This report addresses these issues with regard to the development, operation, and closure activities associated with copper dump leaching operations.

PURPOSE AND SCOPE

The purpose of this report is to describe the characteristics of current copper dump leaching operations in the Western United States. This analysis includes an inventory of active, inactive, and abandoned copper leaching sites and a summary of available environmental impact data from such sites. It also examines current management practices and possible alternative practices that could be used to reduce the environmental impact of copper leaching operations. In addition to dump leaching, other leaching methods that are being used are also described.

The data included in this report were obtained primarily from a literature search and from visits to the major copper leaching operations in the Southwest. The intent of the literature search was to collect information on dump leaching practices, recovery technologies, and the environmental impact of leaching operations in the copper mining industry. State environmental personnel and experts representing such organizations as the Bureau of Mines were also consulted to identify any ongoing research activities dealing with copper leach practices and control technologies. Ten active and inactive copper leach sites were visited to obtain information on the operation and characteristics of the leaching operations. A bibliography of selected references identified during the literature search is included at the end of this report. The findings from the site visits are presented in the trip reports contained in Appendix A.

CONTENT

Section 2 provides an overview of the copper industry and the significance of leaching practices within that industry. It also provides a description of the basic characteristics of copper leaching and presents an inventory of active, inactive, and abandoned sites, including information on the location and production capacity of each of the sites.

Section 3 provides a more detailed description of the copper dump leaching practices currently used in the United States. In addition to a detailed discussion of dump leaching operations (the most prevalent method in the United States), it includes a description of heap, in situ, vat, and agitation leaching operations. Descriptions of methods used to recover copper from solution are also presented.

Section 4 presents a summary of existing monitoring data regarding the environmental impact of copper leaching operations. The summary includes a description of the characteristics of the leaching material, the leaching solutions, and the copper ladden liquids (i.e.,pregnant liquor solutions), which are the primary sources of potential ground-water contamination.

Section 5 presents a discussion on the following management practices that may be used to reduce the potential for ground-water contamination by leachates released by copper dump leaching operations: site characterization and ground-water monitoring techniques, ground-water management systems, surface-water management practices, leachate control systems, and reclamation and closure activities. Illustrative costs associated with the implementation of each of these practices are also presented and discussed.

Section 6 summarizes the information provided in the report and presents conclusions concerning the potential impact of copper leaching operations on human health and the environment and the effect of existing and proposed management practices on surface-water and ground-water contamination. Areas in which additional information is required are also identified.

SECTION 2

OVERVIEW OF LEACHING PRACTICES IN THE COPPER INDUSTRY

Leaching is a hydrometallurgical process that separates a valuable product from the gangue materials or host rock by dissolving the product in a solvent solution. The product is then recovered from solution in a relatively pure form by a chemical or electrolytic process. In the copper industry, dump leaching methods are used to extract copper from ores too low in grade to concentrate by conventional beneficiation and froth flotation. The dissolved copper is subsequently recovered from solution by precipitation onto scrap iron or by solvent extraction and electrowinning. The flow diagram in Figure 1 depicts dump leaching and hydrometallurgical processing of copper.

This section presents an overview of the copper mining industry in the United States and the significance of dump leaching operations to the industry. The chemistry and basic operating characteristics of the leaching methods most commonly practiced in the United States are also described. Finally, a list of currently active, inactive, and abandoned copper leaching sites is presented.

INDUSTRY CHARACTERIZATION

The first use of leaching to recover copper from ores is believed to have occurred in the Rio Tinto area of Spain.[5] Records in that area indicate that concessions were granted for the recovery of copper from leach liquors in 1752.[6] The controlled leaching of uncrushed, low-grade copper ore was not introduced into the United States, however, until 1914.[7] Today, dump leaching is an integral part of most active mining operations.

Copper mining is centered in three States: Arizona, New Mexico, and Utah.[3] Other States where copper is mined include Nevada, Montana, Michigan,

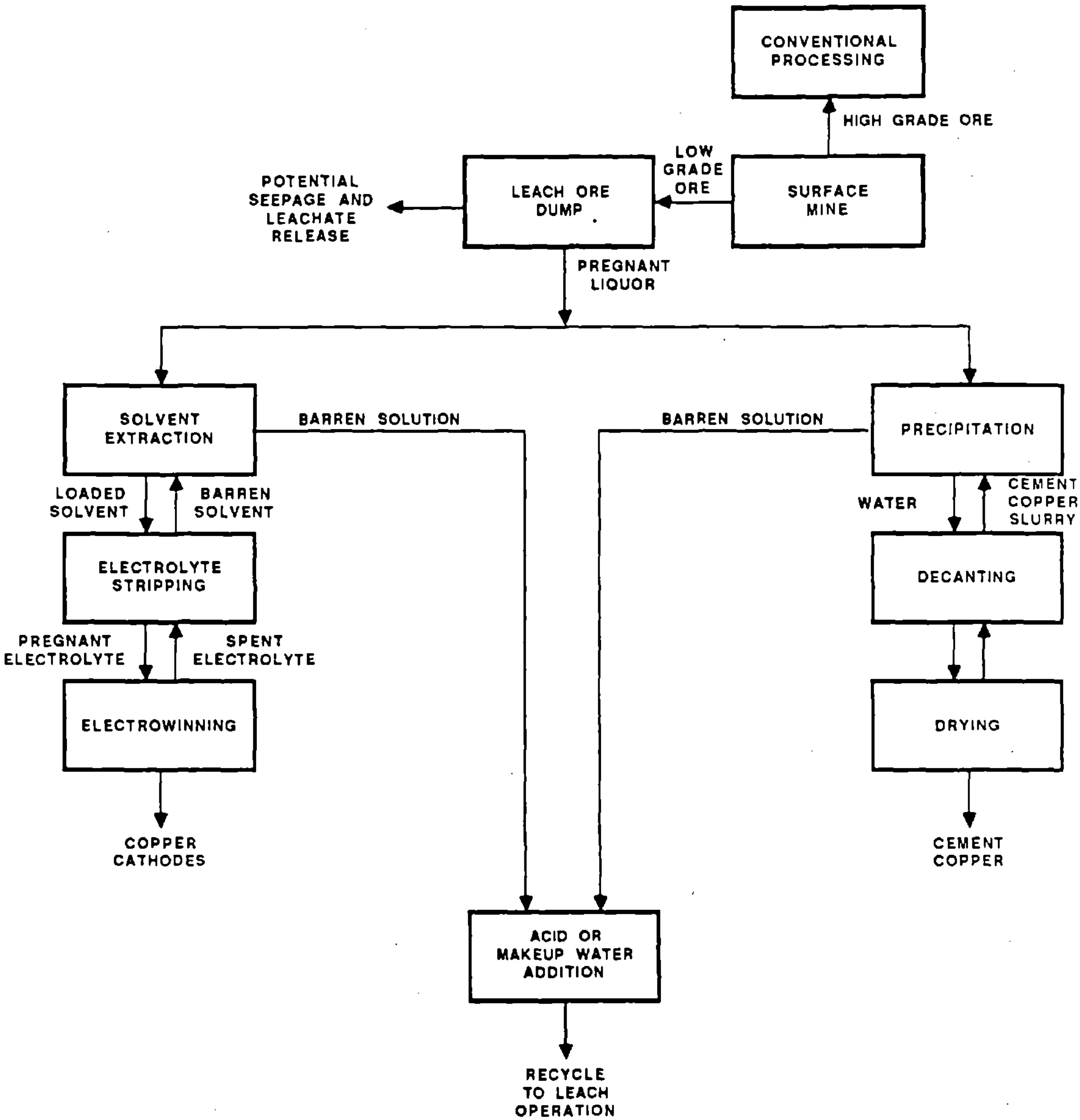

Figure 1. Hydrometallurgical processing of copper.

and Tennessee. Copper is also frequently recovered as a byproduct from the processing of silver, lead, and zinc ores. These operations are centered in Idaho, Missouri, and Tennessee, respectively. In 1985, only 27 primary and 41 byproduct copper mines were active. By comparison, 48 primary and 65 byproduct copper mines were active in 1975 (personal communication from J. L. W. Jolly, U.S. Bureau of Mines, Washington, D.C., August 1986). The number of active copper mines in the United States has and continues to decline because of world overproduction and accompanying low prices.[8]

Of the active operations, surface mining accounts for approximately 90 percent of the copper ore produced annually.[9] This method of mining displaces enormous amounts of soil and rock in the process of gaining access to and exploiting the principal ore body. In 1983, more than 234 million metric tons of such waste rock was generated by copper mining operations.[10] In Arizona alone, about 2.5 billion metric tons of waste rock were generated during the 10-year period from 1975 to 1984 (personal communication from J. B. Hiskey, Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona, August 20, 1986). Because much of this material contains small amounts of copper (less than 0.3 percent), it is often segregated from the barren waste rock, deposited in huge dumps adjacent to the mine pit, and leached with a dilute acid solution to recover additional copper values. Cement copper (copper that has been recovered from the leach solution by precipitation onto iron) generally requires smelting and refining by conventional means to produce high-grade copper. The cathode copper obtained by electrowinning, however, is generally of sufficient grade for direct casting without additional processing. Many of the larger copper-producing companies are fully integrated from mine to refinery.[8]

Table 1 presents annual primary copper production figures for 1975 through 1984. Although total primary production has declined over the last 10 years, the percentage of copper produced by leaching operations has increased during the same period. In the future, as lower grade ores are mined and the costs of conventional milling and smelting continue to rise, leaching is expected to account for an increasing percentage of the total primary copper production in the United States.[10] Some researchers estimate that by

1990 leaching will account for as much as 25 to 30 percent of the annual copper production (personal communication from J. B. Hiskey, Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona, August 20, 1986).

TABLE 1. ANNUAL PRODUCTION OF PRIMARY COPPER, 1975-1984[a]

Year	No. of principal copper mines	Total primary production, metric tons	Precipitate production, metric tons	Electrowon production, metric tons	Combined precipitate and electrowon production, % of total primary production
1975	48	1,280,000	131,000	42,900	13.6
1976	46	1,460,000	114,000	71,900	12.8
1977	44	1,360,000	122,000	81,100	14.9
1978	42	1,360,000	111,000	98,400	15.4
1979	40	1,450,000	127,000	100,000	15.7
1980	41	1,180,000	102,000	118,000	18.6
1981	41	1,540,000	114,000	161,000	17.9
1982	36	1,150,000	105,000	132,000	20.6
1983	31	1,040,000	89,300	102,000	18.4
1984	31	1,090,000	80,800	110,000	17.5

[a] Source: Reference 9.

FUNDAMENTALS OF COPPER LEACHING

In recent years, world overproduction of copper has driven its price to post-World War II lows. Further, stricter environmental laws in this country have increased procuction costs. Hydrometallurgical processing of copper, which has been commercially developed over the last 20 years, provides and economical alternative to conventional smelting and refining operations. These developments have had an important impact on U.S. copper production and have resulted in a significant increase in the application of leaching technology to low-grade ores.

Leaching Methods

Dump leaching is the principal method by which copper values are leached from low-grade (i.e., less than 0.5% copper) ore. Other methods that are used to a lesser extent or are currently under development include heap vat, agitation, and in situ leaching. These methods differ with respect to the degree of site preparation, the type and grade of ore leached, ore preparation, the characteristics of the leach solution, the duration of the leach cycle, and the size of the operation.[11] The salient characteristics of the various leaching methods are summarized in Table 2.

Ores and Reagents

The U.S. copper industry is based predominantly on production from porphyry deposits (large, relatively low-grade occurrences of disseminated mineralization).[12] Copper occurs in these deposits primarily as sulfide or oxide minerals. The principal copper minerals are listed in Table 3. Approximately 90 percent of the copper ore mined in the United States occurs in sulfide ore.[11] Oxide ores originated mainly from supergene chalcocite deposits (those formed by descending solutions). Circulating surface water caused the copper sulfide deposits to oxidize or weather and, under various conditions, to precipitate as copper oxide minerals.

Historically, sulfide and oxide ores containing less than about 0.3 percent copper were deemed too lean in copper to be smelted directly or to be processed into a concentrate. Heating and melting of huge quantities of worthless material would have required too much energy and too great a furnace capacity. Isolation of the copper minerals in a concentrate also would have required considerable amounts of energy for adequate crushing and grinding of the ore and effective separation of the copper from other minerals in the ore. Hence, these materials were generally discarded in large dumps in and around mining sites and were leached as an afterthought. Dump leaching of low-grade ores is an integral part of most current copper mining operations.

The mineralization of these leach materials is important to the leaching process. The type of copper mineral controls the reaction chemistry and the rate at which copper is dissolved. In the case of sulfide ores, pyrite (FeS_2), a common constituent, is important because it leads to the formation of ferric sulfate, sulfuric acid, and heat, which aid in the leaching of the copper minerals.[11] Host rock gangue minerals also have an important role in

TABLE 2. SALIENT CHARACTERISTICS OF COPPER LEACHING METHODS[a]

Leaching method	Mineralization	% Cu in ore	H_2SO_4 concentration in leachant, kg/m³	Cu concentration in pregnant solution, kg/m³	Leach cycle	Representative size of operation	Copper leached, metric tons/day
Dump	Sulfide or mixed oxide/sulfide wastes	0.2-1	1-5	1-2	3-30 years	5 x 10^6 metric tons of ore	100
Heap	Oxide	0.5-1	2-10	2-5	4-6 mos.	3 x 10^5 metric tons of ore	20
In situ	Oxide (with some sulfide)	0.5-1	1-5	1-2	5-25 years	4 x 10^6 metric tons of ore	20
Vat	Oxide	1-2	50-100	30-40	5-10 days	6-12 vats	10-120
Agitation	Oxide (concentrate)	20-30	50-100	30-50	2-5 h	45 leach tanks 47 thickeners	350
	Roaster calcines	30-40	50-100	30-50	2-5 h		

[a] Source: Reference 11.

the leaching of low-grade ores. Gangue minerals can neutralize large quantities of acid and can, by their decomposition, add various species to the leaching solution.

TABLE 3. PRINCIPAL COPPER MINERALS[a]

Mineral	Composition
Sulfides	
Chalcopyrite	$CuFeS_2$
Chalcocite	Cu_2S
Covellite	CuS
Bornite	Cu_5FeS_4
Oxides	
Azurite	$2CuCO_3 \cdot Cu(OH)_2$
Malachite	$CuCO_3 \cdot Cu(OH)_2$
Chrysocolla	$CuSiO_3 \cdot 2H_2O$
Cuprite	Cu_2O

[a] Source: Reference 8.

In dump leaching of sulfide ores, the principal leaching agent is ferric ion generated by autotrophic bacteria (personal communication from M. E. Wadsworth, Dean at the College of Mines and Mineral Industries, University of Utah to Dr. Abron-Robinson of Peter Consultants, Inc., letter dated October 9, 1986). These bacteria generate acid needed for acid-consuming reactions including oxygen reduction. The bacteria also oxidize sulfate and thus form more sulfuric acid. Sulfuric acid also may be added to the barren leach solution applied to the dump. Most leaching operations can obtain sulfuric acid rather inexpensively from copper smelters that produce large amounts of the acid from the sulfur dioxide (SO_2) gases generated in the smelting, roasting, and converting operations. Another advantage of sulfuric acid is that it rapidly solubilizes copper oxides and is regenerated when sulfide minerals are leached. Other leaching agents include solutions of ammonia hydroxide and ammonia carbonate, which enhance the solubility of copper oxides through complex formation, and solutions of ferric sulfate and ferric chloride, which oxidize insoluble copper sulfides to soluble species.

Chemistry of the Leaching Process

The chemistry of leaching copper minerals is well documented.[13] Most oxidized copper ores dissolve rapidly in dilute sulfuric acid. Sulfide minerals, on the other hand, are not soluble in sulfuric acid unless oxidizing conditions exist. Even then, the reaction is much slower unless the oxidizing conditions are very strong.[11] The rate at which copper is leached from dumps is diffusion-controlled. The rate of dissolution depends upon a variety of factors, including the amount of contact area between the leaching solution and the mineral solids, the effect of bacterial activity, the types of copper minerals present, the acid strength, and the reaction temperature.

Some of the reactions by which copper oxide ores are leached with sulfuric acid are presented in Equations 1 through 3. Cuprite and native copper are common nonsulfide minerals that require some oxidation to dissolve the copper. The reactions by which these minerals are dissolved are presented in Equations 4 through 6.[13]

Azurite

$$2CuCO_3 \cdot Cu(OH)_2(s) + 3H_2SO_4(aq) \rightleftarrows 3CuSO_4(aq) + 2CO_2(g) + 4H_2O(l) \quad \text{(Eq. 1)}$$

Malachite

$$CuCO_3 \cdot Cu(OH)_2(s) + 2H_2SO_4(aq) \rightleftarrows 2CuSO_4(aq) + CO_2(g) + 3H_2O(l) \quad \text{(Eq. 2)}$$

Chrysocolla

$$CuSiO_3 \cdot 2H_2O(s) + H_2SO_4(aq) \rightleftarrows CuSO_4(aq) + SiO_2(s) + 3H_2O(l) \quad \text{(Eq. 3)}$$

Cuprite

$$Cu_2O(s) + H_2SO_4(aq) \rightleftarrows CuSO_4(aq) + Cu(s) + H_2O(l) \quad \text{(Eq. 4)}$$

$$Cu_2O(s) + H_2SO_4(aq) + Fe_2(SO_4)_3(aq) \rightleftarrows 2CuSO_4(aq) + H_2O(l) + 2FeSO_4(aq) \quad \text{(Eq. 5)}$$

Native Copper

$$Cu(s) + Fe_2(SO_4)_3(aq) \rightleftarrows CuSO_4(aq) + 2FeSO_4(aq) \quad \text{(Eq. 6)}$$

The oxidizing conditions required for copper sulfide minerals are provided by the presence of ferric sulfate, which is generated when pyrite in the ore is exposed to moisture and oxygen in the atmosphere and to bacterial activity. Some of the primary reactions by which the major copper sulfide minerals are leached are presented in Equations 7 through 12.[13]

Chalcopyrite

$$CuFeS_2(s) + 2Fe_2(SO_4)(aq) = CuSO_4(aq) + 5FeSO_4(aq) + 2S° \quad \text{(Eq. 7)}$$

$$S° + 1.5\ O_2(g) + H_2O + \text{bacterial activity} = H_2SO_4(aq) \quad \text{(Eq. 8)}$$

Chalcocite

$$Cu_2S(s) + Fe_2(SO_4)_3(aq) \rightleftarrows CuS(s) + CuSO_4(aq) + 2FeSO_4(s) \quad \text{(Eq. 9)}$$

$$Cu_2S(s) + 2Fe_2(SO_4)_3(aq) \rightleftarrows 2CuSO_4(aq) + 4FeSO_4(aq) + S(s) \quad \text{(Eq. 10)}$$

Covellite

$$CuS(s) + Fe_2(SO_4)_3(aq) \rightleftarrows CuSO_4(aq) + 2FeSO_4(aq) + S(s) \quad \text{(Eq. 11)}$$

$$CuS(s) + 2O_2(g) \rightleftarrows CuSO_4(aq) \quad \text{(Eq. 12)}$$

The amount of copper released during leaching of low-grade sulfide ores has been found to be directly proportional to the quantity of oxygen reacting with the ore. The rate of oxidation depends on a variety of factors. The rate can be maximized, however, by maintaining the pH of the solution relatively low; the lower the pH, the faster the rate of oxidation. At pH levels above 2.5 to 2.6, the leaching of copper appears to slow considerably.[14]

The process of leaching copper from sulfide minerals requires the presence of autotrophic bacteria. Although the mechanism of this process is not completely understood, it is believed that most sulfide mines contain this bacteria and that use of mine waters for the leach solution provides the initial cultures of the bacteria for the leach systems.[11] Autotrophic bacteria, such as Thiobacillus ferrooxidans, promote the oxidation of pyrite to ferrous sulfate and sulfuric acid, which, in turn, react with the copper sulfide minerals to produce copper sulfate in solution.[13] The bacteria require oxygen to meet metabolic needs. The coupled reactions are:

$$1/2\ O_2(aq) + H_2SO_4(aq) + 2FeSO_4(aq) \overset{bac}{=} Fe_2(SO_4)_3(aq) + H_2O \qquad \text{(Eq. 13)}$$

This reaction is acid-consuming. The bacterial reactions, coupled with other nonbioextractive reactions within the dump, result in a dynamic buffering condition that causes a constant pH.

The production of sulfuric acid is a requirement for effective dump leaching. Acid generation makes it possible for oxygen discharge and ferric ion production to occur under microbial activity. The direct oxidation of pyrite results in the formation of two equivalents of acid per molecule of original pyrite:

$$FeS_2 + 3.5O_2 + H_2O \rightleftarrows Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad \text{(Eq. 14)}$$

In addition, the ferrous iron produced by this reaction undergoes oxidation to ferric iron and precipitates as a hydroxide, which results in two additional acid equivalents:

$$14Fe^{2+} + 3.5O_2 + 14H^+ \rightleftarrows 14Fe^{3+} + 7H_2O \qquad \text{(Eq. 15)}$$

$$Fe^{+3} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \qquad \text{(Eq. 16)}$$

Thus, a total of four equivalents of acid are produced from a single molecule of pyrite.[10] The hydrolysis reaction (Eq. 16) also forms hydrated hematite (boemite) or iron jarosites.

During the active life of a leaching operation, the addition of sulfuric acid may be useful because it offsets acid losses in gangue materials. If the leaching operation is suspended or abandoned, acid may continue to be produced if sufficient water from precipitation is present. As the solution percolates through the ore, it will continue to leach out metals and other potentially toxic ground-water contaminants if the acid generated exceeds the neutralization capacity of the gangue. This process may continue for decades under suitable environmental conditions (e.g., moist climates).

The precipitation of basic iron salts in pipelines, on the surface of dumps, and within the dumps is a problem primarily during the active life of the leaching operation. These salts tend to constrict pipes and form impervious layers within the dumps that restrict the movement of leach solutions. This problem is typically addressed by controlling the pH and iron content of the leach solution.[13] This problem may also be addressed by passing a reducing solution through the pile. Because of the huge volume of solution, however, controlling its chemical balance is very costly. After closure of the operation, the precipitation of iron salts may serve a useful purpose by preventing moisture and leachate generated within the pile from contacting some of the metal-bearing minerals and thereby reducing the acid generation capability of the abandoned leach site and its resulting impact on the environment. The precipitated iron salts and the increased weathering of the rock due to acid reaction with gangue minerals may decrease the permeability of the dump. Natural settling and compression of the dump over time may also decrease its permeability.

Dump leaching refers to the leaching of run-of-mine, low-grade, copper ore that has been deposited on the ground surface without any site preparation. Copper leach dumps are massive. They are typically over 100 feet high and cover hundreds of acres. Dumps are placed in an area where the slope of the native terrain provides the means for collection of pregnant liquor. The leach solution flows by gravity through the dump and then over the slope of the native ground beneath the dump to a collection point, usually a pond, at the downgrade toe of the dump. Historically, dump leaching evolved from secondary efforts to recover copper from waste rock and mine overburden generated by conventional mining methods (principally open-pit operations). Most newer copper mining operations have included recoveries from leaching in premining planning and economic evaluations. In some cases, the ability to recover additional copper by dump leaching may have been a key element in the decision to mine a particular ore body.

In contrast to dump leaching, heap leaching refers to the leaching of low-grade ore that has been deposited on a specially prepared pad (e.g., synthetic, asphalt, or compacted clay pad). In heap leaching, the ore is frequently crushed prior to emplacement. Site-specific characterisitcs determine the nature and extent of the leaching operations used. Other leaching methods are used to lesser extents. In situ leaching involves the leaching of low-grade copper ore without its removal from the ground, i.e., in abandoned underground mine workings, pit walls, and subsidence zones. In some cases, the ore may be prepared for leaching by blasting or hydraulic fracturing. Vat leaching is used to extract copper from crushed, nonporous, oxide ore in large tanks or vats. Agitation leaching involves the rapid leaching of ore concentrate or roaster calcine in agitated tanks. Vat and agitation leaching are generally more rapid, more efficient, and much more costly than dump leaching. Each of these methods is described in greater detail in Section 3.

CHARACTERISTICS AND GEOGRAPHIC DISTRIBUTION OF COPPER LEACHING SITES

As of this writing, there are 18 commercially active copper leaching operations in the United States with a total production capacity of 277,300 metric tons of copper per year (personal communication from J. L. W. Jolly, U.S. Bureau of Mines, Washington, D.C., August 1986). Arizona has 14 active sites, New Mexico has two, and Utah and Nevada each have one. Historically, the southwestern United States has been the principal copper-producing region of the country. The topography of most of the mines in this area is gently rolling to mountainous, vegetation is relatively sparse, and the climate is generally arid to semiarid. The average annual precipitation at most sites is less than 20 inches. As a result, there is very little surface water in these areas, and most leaching operations rely on ground water as a source of water. On the other hand, surface-water runoff from winter snow accumulation around sites in mountainous areas (such as Bingham Canyon, Utah) is much greater than that found in southern Arizona and western New Mexico.[15]

Copper dump and heap leaching sites are located in proximity to the mining operation, as haulage costs quickly offset the value of the copper recovered. The land around most of these mines is primarily undisturbed and vacant, with a few scattered farms and ranches. Livestock grazing and agricultural industries are the primary uses of the land. In some cases, however, the facilities are located near urban or residential areas. For example, Kennecott's Bingham Canyon operation is about 15 miles west of Salt Lake City, and the Inspiration mine is less than 1 mile from the towns of Globe and Miami in eastern Arizona. Table 4 provides an inventory of these active

TABLE 4. INVENTORY OF ACTIVE COPPER LEACHING OPERATIONS IN THE UNITED STATES

Operation	Location	Leaching method					Recovery method		Capacity, metric tons
		Dump	Heap	In situ	Vat	Agitation	Precipitation	SX-EW	
ASARCO, Inc.									
Silver Bell	Marana, Arizona	X					X		6,000
Battle Mountain Gold Co.									
Battle Mountain	Battle Mountain, Nevada	X						X	5,000
Cyprus Minerals Co.									
Bagdad	Bagdad, Arizona	X						X	6,800
Mineral Park	Kingman, Arizona	X					X		3,500
Sierrita/Esperanza	Sahuarita, Arizona	X					X		6,000
Inspiration Consolidated Copper Co.									
Inspiration	Claypool, Arizona	X	X					X	42,000
Oxhide	Claypool, Arizona	X					X		500
Kennecott									
Bingham Canyon	Bingham Canyon, Utah	X					X		36,000
Chino	Santa Rita, New Mexico	X					X		20,000
Ray	Ray, Arizona	X	X	X[a]			X	X	15,000/29,000
Kocide Chemical									
Van Dyke	Casa Grande, Arizona			X[a]					NA[b]
Leaching Technology, Inc.									
Nacimiento	Cuba, New Mexico			X[a]					NA
Newmont Mining Co.									
Miami Leach	Miami, Arizona			X				X	5,000
Pinto Valley	Miami, Arizona	X						X	16,000
San Manuel	San Manuel, Arizona		X					X	25,000
Noranda Lakeshore Mines, Inc.									
Lakeshore	Casa Grande, Arizona			X				X	10,000
Phelps Dodge Corp.									
Copper Queen	Bisbee, Arizona	X		X			X		2,500
Morenci/Metcalf	Morenci, Arizona	X					X		10,000
Tyrone	Tyrone, New Mexico	X					X	X	5,000/30,000

[a]Experimental only.
[b]NA - not available.

operations. Figure 2 shows the geographic distribution of the active leaching operations in the Western States.

Table 5 provides an inventory of the inactive and abandoned copper leaching sites in the United States. These sites currently number about 23, including one new site that is in the permitting stage. It is difficult to assess the precise number of abandoned leaching operations. Many of the sites are very small and ceased operation many years ago. Others that are now closed may not be permanently abandoned. Just as dumps containing what was once considered waste rock are now being leached, improved leaching techniques and copper recovery methods may result in the reactivation of currently inactive sites. Also, rising copper prices may make the operation of an inactive site economically feasible once again. In this case, production would likely resume. Figure 3 shows the geographic distribution of the inactive and abandoned leaching operations identified in the Western States.

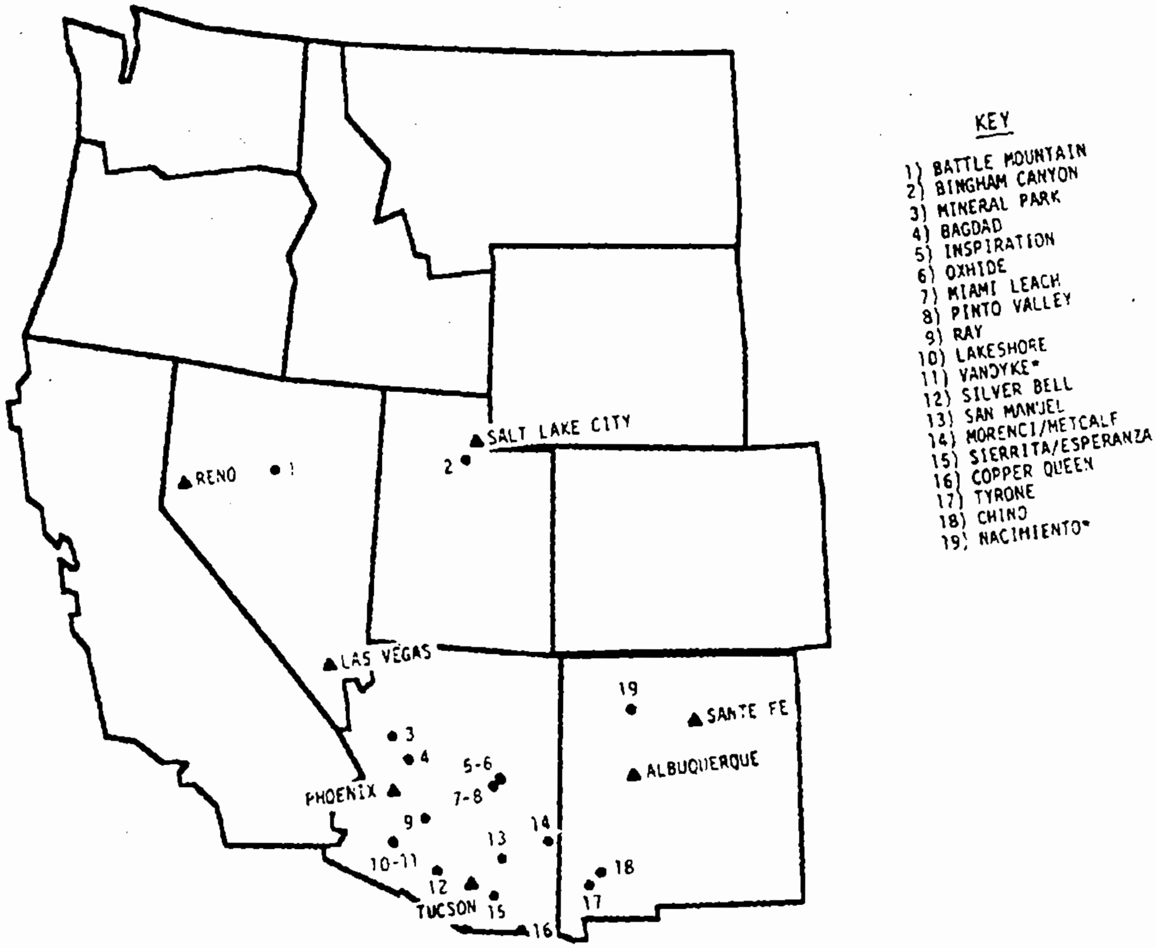

Figure 2. Geographic distribution of active copper leaching operations in the United States.

TABLE 5. INVENTORY OF INACTIVE COPPER LEACHING OPERATIONS IN THE UNITED STATES

Operation	Location	Leaching method					Recovery method		Capacity, metric tons
		Dump	Heap	In situ	Vat	Agitation	Precipitation	SX-EW	
The Anaconda Minerals Co.									
Yerrington	Weed Heights, Nevada	X			X				NA[a]
Anamax Mining Co.									
Twin Buttes	Sahuarita, Arizona	X	X					X	33,000
ASARCO, Inc.									
San Xavier	Sahuarita, Arizona	X			X				NA
Cochise Mining Corp.									
Peacock	Safford, Arizona		X						NA
Cyprus Minerals Co.									
Johnson	Benson, Arizona		X					X	4,000
Essex International, Inc.									
Milford	Milford, Utah				X				NA
Inspiration Consolidated Copper Co.									
Bluebird	Claypool, Arizona		X					X	7,300
Inspiration	Claypool, Arizona			X	X				NA
Kelmine Corp.									
Lisbon Valley[b]	Moab, Utah		X						NA
Kennecott									
Kimberly-Sunshine	Ely, Nevada	X							NA
Ray	Ray, Arizona				X	X			NA
McAlester Fuel Co.									
Zonia	Kirkland, Arizona		X	X					NA
Newmont Mining Co.									
Copper Cities	Miami, Arizona	X					X		2,000
Noranda Lakeshore Mines, Inc.									
Lakeshore	Casa Grande, Arizona				X	X			NA
Ohio Copper Co.									
Ohio Copper	Bingham Canyon, Utah			X					NA

(continued)

TABLE 5 (continued)

Operation	Location	Leaching method: Dump	Leaching method: Heap	Leaching method: In situ	Leaching method: Vat	Leaching method: Agitation	Recovery method: Precipitation	Recovery method: SX-EW	Capacity, metric tons
Osceola Gold and Silver, Inc.									
Rio Tinto	Mountain City, Nevada		X						NA
Phelps Dodge Corp.									
New Cornelia (Ajo)	Ajo, Arizona	X					X		500
United Verde	Jerome, Arizona	X							NA
Ranchers Exploration and Development Corp.									
Big Mike	Winnemucca, Nevada		X	X					NA
Old Reliable	Mammoth, Arizona			X					NA
Washington Corp.									
Arbiter Leach	Butte, Montana							X	NA
Berkeley	Butte, Montana	X					X		10,000
Butte Hill Leach	Butte, Montana			X			X		10,000

[a]NA - not available.
[b]Permitting stage.

KEY

1) ARBITER LEACH
2) BERKELEY
3) BUTTE HILL LEACH
4) RIO TINTO
5) BIG MIKE
6) YERRINGTON
7) KIMBERLY/SUNSHINE
8) OHIO COPPER
9) MILLFORD
10) LISBON VALLEY
11) UNITED VERDE
12) ZONIA
13) BLUEBIRD
14) INSPIRATION
15) COPPER CITIES
16) RAY
17) LAKESHORE
18) NEW CORNELIA (AJO)
19) OLD RELIABLE
20) PEACOCK
21) JOHNSON
22) SAN XAVIER
23) TWIN BUTTES

Figure 3. Geographic distribution of inactive copper leaching operations in the United States.

SECTION 3

DESIGN AND OPERATION OF COPPER LEACHING SYSTEMS

This section discusses the design and operating characteristics of typical dump leaching systems. It includes a detailed description of the site characteristics, construction practices, leaching solution, and process steps. A brief discussion of heap, in situ, vat, and agititation leaching is also presented. The section concludes with a description of recovery of copper from solution by the cementation and solvent extraction recovery processes.

DUMP LEACHING

Dump leaching refers to percolation leaching of copper from run-of-mine low-grade ores that has been piled on unprepared ground. Enormous quantities of mine overburden and of nonmill-grade ore (i.e., <0.5% copper) have been accumulated and leached in dumps around copper mining sites. The leach cycle for this type of operation is extremely long, usually measured in decades. Current operations place leach-grade ore on their dumps in contrast to older operations that leached former waste dumps. When an ore body is such that mill-grade ore, leach-grade ore, and waste rock containing insufficient copper for economical recovery can each be mined separately, a waste dump is constructed in addition to a leach operation. Because ore characteristics change gradationally rather than abruptly, however, such segregation is not always possible. In these cases, the cost in time and analyses required to define what is leach ore and what is waste may be greater than the opera- tional cost savings. Therefore, operations may opt to put all nonmill-grade ore in a leach dump (personal communication from N. Greenwald, Newmont Serv- ices, Ltd., October 30, 1986).

Site Selection and Preparation

Leach dumps are located adjacent to the mine site to minimize haulage costs and to increase the economic efficiency of the operation. Naturally sloping terrain is selected to facilitate the collection and recovery of the pregnant leach liquors.

When many of the older dumps were started, the dump leaching of copper from low-grade sulfide ores was not practiced; therefore, the overburden containing these minerals was treated as mine waste. As a result, the characteristics of the sites chosen to dump this material was not a major factor in the selection process. In recent years, the leaching of low-grade ores has become an integral part of the copper production process at most copper mining operations. Greater importance has been placed on the selection of sites (e.g., suitable slopes, low permeability, proximity to ground water and surface water are considered). Because of haulage costs, however, potential sites are limited to those in the immediate vicinity of the mine.

Pile Size and Construction

Leach dumps typically cover hundreds of hectares, rise to heights of 60 meters or more, and contain several million metric tons of uncrushed, low-grade ore (Figure 4). The copper content of material deposited in leach dumps averages about 0.3 percent.[13] The materials generally vary considerably in particle size, from large angular blocks of hard rock to highly weathered fine-grained soils. Most of the material is less than 0.6 meter in diameter.[16]

In most dump leach operations, the material is hauled to the top of the dump by trucks. Bulldozers are used to level the surfaces and edges of the dump. The material is typically deposited by end-dumping in lifts on top of an existing dump that has already been leached. Large dumps are usually raised in lifts of 15 to 30 meters. Some sorting of materials occurs when this method of deposition is used. Coarser fragments tend to roll down to the bottom of the slope, whereas finer materials accumulate near the surface of the dump. A degree of compacting in the top meter of each lift results from the heavy equipment and truck traffic. After the lift is completed, the top layer is scarified (by a bulldozer and ripper) to facilitate infiltration of the leach solution.[17]

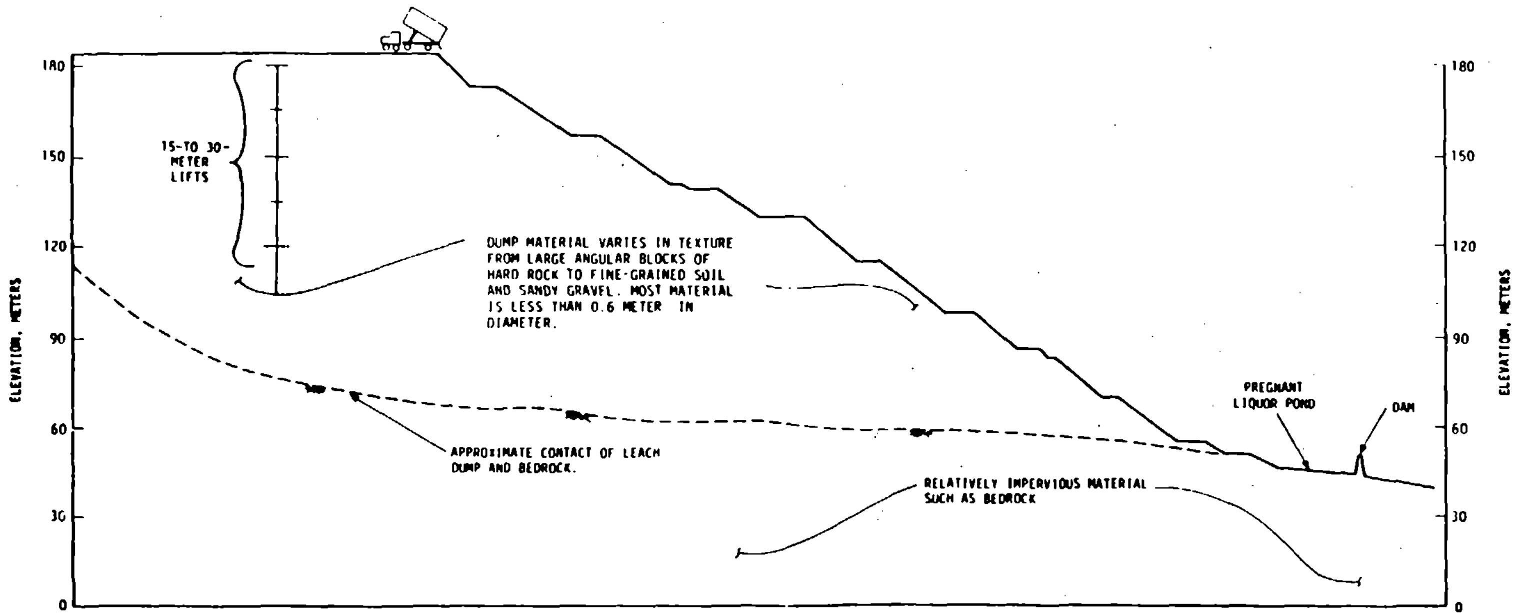

Figure 4. Typical leach dump.

Most leach dumps begin to settle as they are built and continue to settle after the leach solutions have been applied. This continued settling results in part from the percolating liquid moving finer particles into the void spaces between larger particles. The dump is also compressed by the added weight of the solutions and the destruction of the competency of the bridging rocks by chemical reactions that decrepitate the rock.[17]

Characteristics of the Leach Solution

The leach solution for dump leaching of low-grade copper ores typically consists of the barren solution from the precipitation or solvent extraction process used to recover the copper from the pregnant leach liquor plus makeup water to replenish water lost by evaporation and seepage. Sulfuric acid also may be added; however, the need for extra acid for sulfate ores characteristic of the Western United States is controversial (personal communication from M. W. Wadsworth, University of Utah, to Peer Consultants, October 6, 1986). Frequently, only makeup water is added because the bacterial activity on the sulfide minerals that predominate within the dump generates the necessary acid in the leach solution. The typical rate of application of leaching solution on copper dumps is on the order of 0.01 to 0.05 m^3 of leachant per day per square meter of horizontal surface.[11,13]

Process Description

Leach solutions are introduced onto or into dumps by a variety of methods. These include:

1) Flooding the surface by use of a series of small diked ponds.

2) Spraying the solution from hoses or through metal or plastic sprinkler heads.

3) Injecting the solution through holes drilled in the dump and cased with perforated plastic pipe.

4) A combination of these methods.

The distribution method depends on the climatic conditions, dump height, surface area, scale of operation, mineralogy, and size of the leach material.[13]

Because most distribution methods do not provide completely uniform coverage, the application rate of the solution to the dump will vary. The application rate is generally defined as the volumetric flow rate of the leach solution divided by the surface area to which the solution is actually being applied. The average applicaton rate varies between 20 liters/m^2 per hour for sprinklers to as much as 200 liters/m^2 per hour for pond leaching.[18]

In practice, most dumps are leached in sections. The leaching period for each section generally takes 4 to 6 weeks, depending on the efficiency of the surface infiltration. Leaching is generally stopped when either the copper content of the pregnant liquor from the section falls below a predetermined concentration or when permeability diminishes because of the accumulation of decomposed clay materials and iron salt precipitates. After leaching of a section has been discontinued, the surface is scarified by ripping, and either the leaching process is resumed or another lift is begun on the surface. The alternate wetting and resting during the leach cycle promotes efficient leaching of sulfide minerals within the dump.[13]

Under the influence of gravity, the leaching solution percolates down through the ore and carries the dissolved copper along with it. Total distribution of the leach solution throughout a dump, however, is difficult to achieve. In sloped areas, channeling of the solution down the slope accelerates runoff. Within the dump, alternate layering of coarse and fine materials as a result of poor dump construction promotes horizontal solution flow, which may result in the discharge of the copper-bearing liquor from the sides of the dump rather than from the base. The total volume of leach solutions added to dumps must be limited to prevent certain areas, particularly the sloped areas, from becoming saturated. Excess moisture in the pile can lead to slumping of large tonnages of material.[17]

When the pregnant leach solution reaches the bottom of the dump, it flows over the native ground into a collection channel and/or holding pond at the downgrade toe of the dump. Holding ponds are generally located in natural drainage basins enclosed by a dam. The pregnant solution is pumped from the dam to the precipitation or solvent extraction plant, where the copper is recovered from solution.

HEAP LEACHING

Design and Construction

Heap leaching involves placement of leach-grade ore, which has typically been crushed, on a specially prepared surface (i.e., a pad). Because heaps are smaller than dumps, the use of low-permeability pads is permitted. (The use of such pads under dumps is prohibited because the weight of massive dumps would likely result in movement exceeding the shear strength of liner materials.) The application of heap leaching is determined by site-specific economics. Heap leaching is generally practiced with oxide ores because these types of deposits are smaller; because oxides leach more rapidly than sulfides, which allows quicker cost recoveries; and because the oxide leachate has a higher copper constant than sulfide leachate, which provides greater incentive to recover as much solution as possible (personal communication from N. Greenwald, Newmont Services, Ltd., October 30, 1986).

Site preparation involves clearing the site of vegetation and grading the surface toward a collection sump. The native soil may be treated with some type of binder, or a natural (clay), asphalt, or synthetic (e.g., polyethylene) liner may be installed.[13]

Heaps are much smaller than copper leach dumps. On the average, they contain between 100,000 and 500,000 metric tons of ore. Because the ore is crushed, the size of the particles in the leach material is also considerably smaller--generally less than 10 cm in diameter.[13] Copper values are generally 1 percent or better.

In most heap leaching operations, the ore is blasted or ripped from surface deposits and then hauled to the heap in trucks. Heap leach piles are generally built in lifts of 4 to 6 meters. The size of the lifts will vary, however, depending on the size of the particles in the leach material. As the average particle size decreases, the size of each lift is generally reduced to improve extraction rates. An optimum lift height is believed to exist for ore within a given particle size range.[7]

Because of the relatively high copper content of the oxide ore and the size of the particles in the leach material, copper heaps are designed and operated to minimize truck traffic and dozer work on the surface. The purpose of such procedures is to reduce the compaction resulting from these activities and thereby improve the permeability of the heap.

One method of constructing a new heap involves placement of the leach material in a strip along the centerline of the new heap. Subsequent loads are then dumped along the outer edge of the strip and pushed over the side with a bulldozer to build the heap to its full width. With this method of material emplacement, only the top meter of the heap becomes compacted. This layer is subsequently scarified to promote infiltration of the leach solution.[13]

Characteristics of the Leach Solution

Sulfuric acid is the lixiviant used in heap leaching. The rate of leaching is proportional to the acid concentration (up to 5 percent H_2SO_4 is used). The acid strength of the leach solution varies proportionately with the rate of leaching, the grade of the copper ore leached, and the amount of acid-consuming gangue present in the ore.[10] The pregnant liquors produced by heap leaching are generally much higher in copper content than those produced by dump leaching because ore grades are higher, the acid solutions are stronger, and the leach materials contain higher proportions of readily soluble oxide minerals.[10]

Process Description

Leach solutions are introduced onto or into the heaps in much the same manner as they are in dump leaching operations; i.e., by flooding, spraying, or injecting the solution or by a combination of these methods.

Heap leaching is a relatively continuous process. Alternate wetting and aerating of the leach material is generally unnecessary because the dissolution of copper in oxide minerals does not require oxidation and because surface infiltration and subsurface flow are relatively unaffected by the precipitation of iron oxide. The mechanical action of the droplets of leach solution contacting the heap surface, however, will cause some decrepitation of the ore and compaction of the surface and will promote crust formation.[3] Leaching is generally stopped after a given period dictated by the leaching cycle or when the copper content of the pregnant liquor falls below a predetermined concentration. When no further leaching occurs, the surface of the area is scarified by ripping and another lift is begun on the surface.

The heap leaching cycle typically lasts between 60 and 180 days. The solution percolates through the ore and dissolves the copper minerals along its path. The total distribution of leach solution throughout a heap, however, is more easily achieved than in leach dumps because of the greater consistency of the size and distribution of particles within the heap and the absence of channeling caused by iron salt precipitates. The total volume of leach solutions added to dumps still must be limited to prevent areas from becoming saturated.

When the pregnant leach solution reaches the bottom of the heap, it flows over the pad into a collection trough and/or holding pond, from which it is pumped to a precipitation or solvent extraction plant for recovery of the copper from solution.

OTHER LEACHING PROCESSES

In Situ Leaching

In situ leaching, also called solution mining, refers to the leaching of low-grade copper ore without removing it from the ground. The economics of current mining and recovery methods often prevents the mining of ore that either contains insufficient metal values or entails extensive site preparation or operating expense. For this reason, the use of the in situ method is increasing as a means of recovering additional copper from old mine workings (open pits, block caved areas, backfilled stopes) from which the primary sulfide deposit has been removed. These types of operations tend to leave behind considerable fractured copper-bearing rock that is uneconomical to mine and recover by conventional means. In situ leaching is also being considered as a method for extracting copper from deposits that have been fragmented by blasting, previous block-caving mining, or hydrofacting.[19] It should also be applicable to highly porous deposits without fragmentation.

Most abandoned underground mining operations leave halos of low-grade ore surrounding tunnels, stopes, rises, and pillars, and the engineering required in such mines normally provides the basic needs for a leaching operation. The main shaft is almost always used as a main drainage reservoir. Because tunnels always run upgrade, water or leach solutions flow naturally by gravity to the main shaft for recovery. Fluids flowing from the extraction drifts and haulage drifts are usually collected behind a dam placed across the main shaft and pumped to the surface.[14] The block caving process causes the area above the cave to fracture and expand in volume, which results in a greater porosity of the mineralized ore body than in the surrounding undisturbed rock. Good examples of this technique may be found at the Lakeshore mine near Casa Grande, Arizona, and the Miami mine in Miami, Arizona.

The chemistry of in situ leaching is similar to that of dump leaching of sulfidic ores and heap leaching of oxidized ores. So that the solution will be exposed to as much mineralization as possible, the ore body must have adequate permeability. Although natural fractures and interconnected pore spaces may increase the porosity, blasting, caving, and hydrofacing also may be required. As noted, the subsidence of material around block caving operations may create sufficient fracturing to make in situ leaching feasible. The leaching solution can be applied to the area either by percolation (using spraying or flooding) or by injection techniques. As the leach solution percolates through the ore, it dissolves the copper minerals, and the resultant pregnant liquor is collected from recovery wells or underground workings.[18] Because copper may be leached from both oxide and sulfide minerals, the leaching process may continue for several years.[13]

In situ leaching can be very economical when applied to previously mined ore zones, but it is very expensive when applied to new ores. The impact on the surrounding environment is lowered when the ore body is surrounded by a low-permeability layer that minimizes the loss of leach solutions. To be successful, an in situ leaching operation generally must have the following characteristics:

- Host rock that does not consume acid
- Host rock that will not decrepitate to seal intrarock fractures
- Sufficient rock fracturing to permit solution to reach copper minerals
- Copper minerals concentrated along fracture rock
- Copper minerals that dissolve within required time
- Ability to recirculate the solution through the ore
- Availability of adequate water[19]

For effective leaching of sulfide ores, good aeration and active bacteria are required, as in dump leaching.

Vat Leaching

Vat leaching is used to extract copper from predominantly oxide ores by subjecting the ore to concentrated sulfuric acid in a series of large tanks or vats. Vat leaching has been preferred to heap leaching in cases where high-grade ore requires crushing to permit adequate contact between the leach solution and the copper minerals. The advantages of this method are high copper extraction rates, short leach cycles, and negligible solution losses.[13]

To expose the copper minerals, the ore is crushed to an approximate size of less than 1 cm and screened to separate the fines (which prevent good distribution of the leach solution) before it is placed into the vats.[13] Most vat leaching operations use several large rectangular tanks having floors that act as filters to facilitate the upflow and downflow of solutions.[20] A typical vat measures 25 meters long, 15 meters wide, and 6 meters deep and contains between 3000 and 5000 metric tons of material. Vat leaching is a batch countercurrent operation with a complete cycle that involves vat loading; ore leaching, washing, draining; and vat excavating. The overall cycle may take 10 to 14 days. The pregnant solutions collected from the most recently filled vats are sufficiently high in copper to permit the direct recovery of copper by electrowinning. The pregnant liquor solution may be sent to a solvent extraction step prior to electrowinning, however, if the iron content of the solution is high. Iron reduces the efficiency in the electrowinning process, and solvent extraction can eliminate this problem. The solutions from the remaining soaks are recycled as leachant for subsequent batches of fresh ore. Continuous leaching, a method in which the leachant continuously flows through the ore in a sequence of vats, has also been practiced.[11] Factors that affect the leach rate (in both batch and continuous leaching) include particle size and porosity, temperature, and acid strength.

Agitation Leaching

Agitation leaching refers to the rapid leaching of fine particles of oxide ore or roaster calcines with a strong sulfuric acid solution in agitated tanks. This leaching method has been used primarily in conjunction with vat leaching operations to recover copper from the fines filtered out of the vat material. Additional lean material is crushed and ground to a fine particle size (90 percent less than 75 μm) and combined with the fines from the vat operation. This material is then mixed with the leach solution to form a pulp or a slurry having a density of between 30 and 40 percent. The mixture is agitated by air or mechanical means in a series of three or six tanks (volume 50-200 m^3) for a period of 2 to 5 hours. Upon completion of the leach cycle, the pregnant liquor is separated from the acid-insoluble residue by cocurrent or countercurrent washing.[11]

Because of the fine particle size of the solids, the strength of the acid solution, and the agitation of the leach slurry, which promotes better liquid-solid contact, agitation leaching has the highest level of copper extraction (in some instances greater than 95 percent extraction).[11]

COPPER RECOVERY PROCESSES

The traditional method for processing and recovering copper from heap and dump leaching operations has been cementation. The main advantage of cementation is its simplicity. The process uses scrap iron to precipitate copper from the pregnant leach solution according to the following substitution reaction:[6]

$$Fe + CuSO_4 \rightleftarrows Cu + FeSO_4 \qquad \text{(Eq. 17)}$$

The copper precipitates on the iron surfaces and is detached in flake or powder form under the influence of the solution flow. The overall recovery of copper is approximately 90 percent, and the precipitate generally contains between 85 and 90 percent copper.[21] The recovered copper is relatively impure, however, and subsequent refining is required, usually by smelting and electro-refinning.

One of the problems with the cementation process is that some of the iron scrap dissolves into the pregnant leach liquor as the copper is being removed. Iron is consumed according to the following reactions:

$$Fe + Fe_2(SO_4)_3 \rightleftarrows 3FeSO_4 \qquad \text{(Eq. 18)}$$

$$Fe + H_2SO_4 \rightleftarrows FeSO_4 + H_2 \qquad \text{(Eq. 19)}$$

Inasmuch as the barren solution produced by this process is generally returned to the top of the leach pile as part of the leaching solution, the precipitation of iron salts on the surface of the dump is exacerbated, which significantly restricts the passage of leaching solution into the dump.

A typical precipitation plant, illustrated in Figure 5, uses gravity launders constructed of concrete. Wood and/or stainless steel gratings are used to divert solution flow and support the iron precipitant. The launders are charged with iron scrap by a variety of mechanical means, including belt conveyors, crane-mounted magnets, and clamshell buckets. Solution is introduced at the upper end of the plant and allowed to trickle downward through the scrap by gravity. Most plants precipitate more than 60 percent of the recoverable copper in the first few launders. The iron scrap in these launders is washed with high-pressure streams of water several times a week to remove the copper. Copper precipitated in the remaining launders is usually removed from once a week to once a month. The barren solution is discharged by gravity from the lower end of the plant.[13]

The resultant slurry of water from the washing process is emptied into decant basins through drain valves, and the cement copper is allowed to settle. The clear water is decanted and returned to the launders. The cement copper is removed from the basins by various mechanical means and dried (e.g., on concrete drying pads) before being shipped to a smelter or other market.

In recent years, solvent extraction increasingly has been used for selective recovery of copper from the dilute leach liquors, particularly those recovered from low-grade dump leaching operations. Although the capital cost of building a solvent extraction (SX) plant is significantly higher than that required to build a cementation plant, the problems associated with the buildup of iron precipitates in the leaching solution are eliminated. Also, the continually rising cost of iron scrap may make the operation of an SX plant more economical.[11]

In solvent extraction, an organic solvent containing a copper-specific chelating agent that complexes wtih copper ion is used to extract the copper from the leach solution, after which the copper is stripped from the organic phase by a strong acid solution. The resultant solution contains a high concentration of copper that serves as an electrolyte for electrowinning.

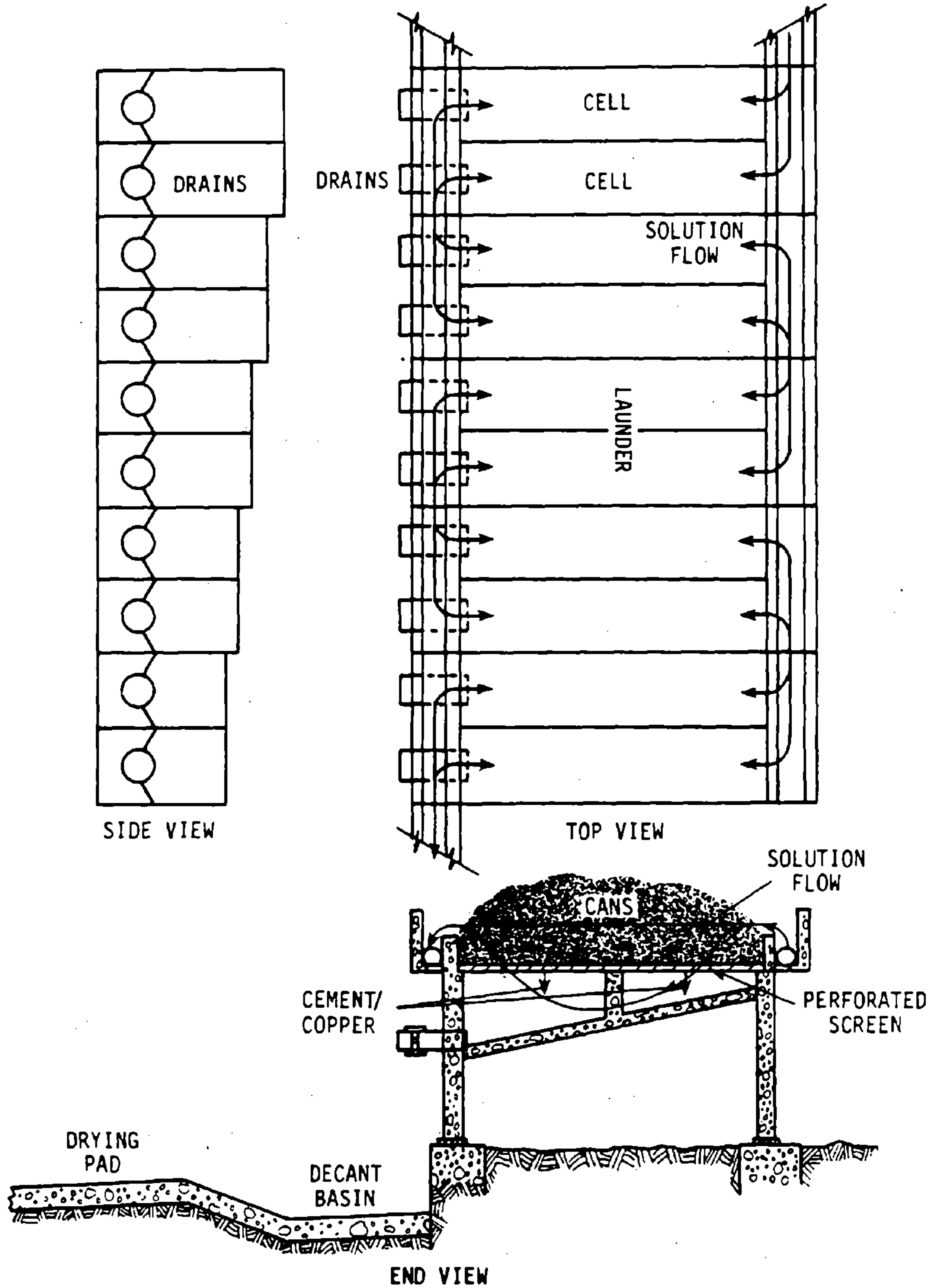

Figure 5. Typical precipitation plant.

Source: Reference 13.

Various chelating agents are currently in use. Solvent extraction requires chelates that have a greater affinity for copper than for other metals. So that a low-viscosity liquid can be obtained, the chelating agents are always dissolved (5 to 20 percent by volume) in an organic carrier such as kerosene. A modifier is often added to improve reaction rates and phase separation.[11]

The extraction of copper from the leach solution into an immiscible organic phase is usually accomplished in a series of mixer/settler stages. The mixing stage causes the leach solution to contact the unloaded solvent. This produces an emulsion, which is pumped into a settling tank, where the loaded organic phase and the barren solution (raffinate) are separated by gravity. The loaded organic phase is then stripped of its copper by a high-acid aqueous phase. The concentration of acid in this aqueous phase is much greater than that of the original leach solution (150 to 185 kg/m H_2SO_4) and is suitable for electrowinning high-purity copper cathodes. The raffinate (which contains almost all of the impurity metals in the original pregnant liquor solution) is returned to the leach operation for further use.[11] Figure 6 illustrates a typical solvent extraction/electrowinning plant.

Typically, the area selected for a solvent extraction plant is located above the proposed raffinate pond so that any spills or overflows from the process will drain into the pond and be recovered. Newer facilities locate the mixers and settlers on concrete pads at ground level. The associated tank farm and related equipment are located in a hole lined with gunite or some other impervious material. A typical plant includes extract settlers and strip settlers with primary and auxiliary mixers, a diluent (generally kerosene) storage tank, a barren or stripped organic storage tank, an electrolyte coalescer, and a series of tanks used in connection with back washing, crud (a semisolid residue formed in the mixers/settlers by the reaction of the solvent with organic constituents in the leaching solution) processing, pH neutralization, and emergency dumping.

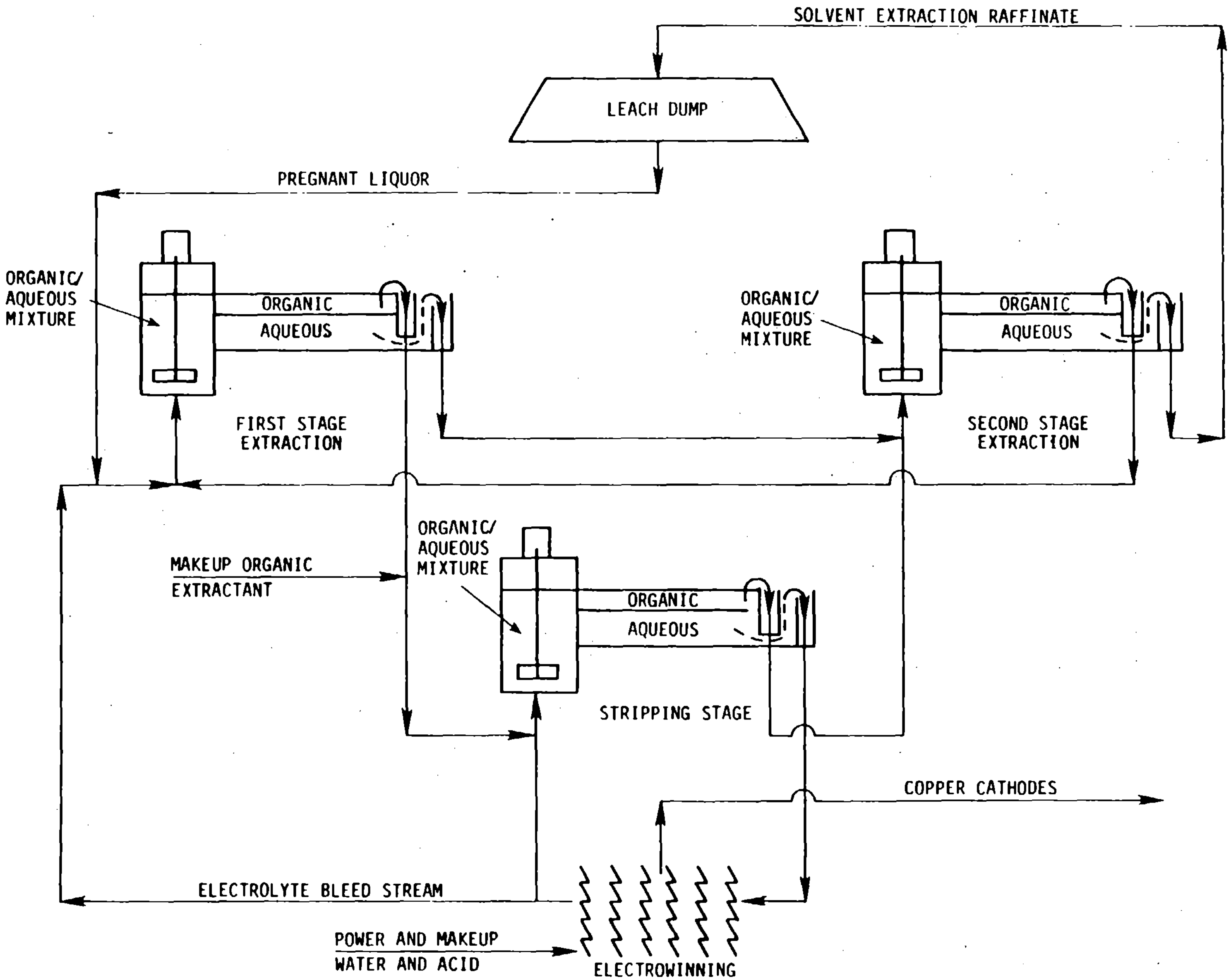

Figure 6. Typical solvent extraction/electrowinning plant.

Source: Courtesy of Phelps Dodge Corporation.

SECTION 4

POTENTIAL FOR ENVIRONMENTAL IMPACT

This section discusses the potential impact of copper leaching operations on the environment. An initial environment assessment requires identification of the mechanisms that could result in the release of contaminants. These mechanisms may be a natural part of the leaching operation or the unintended effect of outside influences or unexpected events. Generally, the most significant mechanisms are those related to a natural part of the leaching operation, as they are the most difficult to change and will have the greatest long-term impact on the environment. Mitigative systems designed to control these types of releases may be required to function for years or even decades. Consequently, the cost of constructing and maintaining such systems may be relatively unlimited. On the other hand, changes in the uses or characteristics of the land surrounding a leaching site or unexpected failures within the leaching circuit itself tend to have a relatively short-term impact on the environment. Although an immediate response may be required, the cost of implementing and maintaining the mitigative activities is generally limited.

After the release mechanisms from the leaching operation have been identified, the potential constituents of the released substances are discussed. These generally depend on the characteristics of the leach material, the nature of the leaching solution, and the type of copper recovery process used in the operation. The mobility of many metals and other minerals is enhanced by the low-pH solutions typically generated in leaching operations. The mobility of minerals in the leach material may also be enhanced by contaminants introduced by the copper recovery process and leaching solution. The actual characteristics of the potential releases from a copper leaching operation also are affected, however, by other site-specific factors that may offset the impact of these processes and minimize the potential harmful effects of the release. It is not feasible to quantify national source terms for acid released from these wastes.[10] Such data are highly site-specific and generally unavailable.[10]

The final portion of this section reviews actual environmental monitoring data gathered from sites in the Southwest. A brief discussion of each site and a summary of the monitoring results are provided.

POTENTIAL MECHANISMS FOR THE RELEASE OF CONTAMINATION

Most copper dump leaching operations are designed to be closed systems; the pregnant liquor from the leach pile is pumped to the copper recovery process, and the barren aqueous solution discharged from the copper recovery process is recycled back onto the leach pile. Nevertheless, these systems include the following potential mechanisms for the release of contamination into the ground water:

- Seepage of acid solutions through soils or liners beneath the leach piles
- Leakage from solution holding ponds and transfer channels
- Spills from ruptured pipes and copper-recovery equipment
- Pond overflow or solution discharge caused by excessive liquid in the solution cycle
- Failure of the dams or liners of solution holding ponds.[10]

Seepage can occur from leach dumps, holding ponds, and transfer channels because most are built directly on the existing topography. Natural drainage basins are generally used to convey and hold the leach solutions. The permeability of the surfaces on which these were built and the resulting environmental impact generally were not investigated extensively at sites selected prior to around 1970. Ravines and gullies were usually selected because they were the shortest and most easily traversed distance from the mine operation. Since 1970, however, the shrinking price of copper, coupled with increased concerns about the environmental impact of copper leaching operations, has spurred efforts to improve the efficiency of these operations. As a result, most new dumps are located on relatively impermeable ground and the drainage pattern is designed to allow the easiest and most effective collection of leach solution.

Excessive liquid in the solution cycle, a potential release mechanism, can occur as a result of changes in climatic conditions, unusual storm events, or mechanical equipment failure. Because most leach piles are located in natural drainage basins, runoff from rainfall and snow melt within these basins will increase the flow rates of liquids into the holding ponds. If this additional flow cannot be handled by the copper recovery process or be diverted into secondary containment areas, the liquid may overflow the banks of the pond onto the surrounding property. A similar problem may arise if the pumping equipment used to drain the holding ponds malfunctions as a result of mechanical malfunction or power failure.

The failure of transfer pipes or holding pond dams and liners can be attributed to a variety of factors. These may include weathering and decomposition caused by contact with the acid leaching solutions and exposure to air. Seismic activity, rock slides, and operator error are also potential failure mechanisms.

SOURCES AND CHARACTERISTICS OF POTENTIAL GROUND-WATER CONTAMINATION

Spent Leach Material

When the copper content of the pregnant liquor from dump leaching operations drops below a value that can be economically recovered, leaching of the ore/waste rock is discontinued. Because of the enormous size of the leach dumps, the spent leach material usually is not removed after operations have ceased. In areas where evaporation exceeds precipitation (as in the desert Southwest where most dumps are located), the leach piles tend to dry out over a period of several months. Because of the huge absorptive capacity of these piles, many inactive leach dumps and heaps do not generate leachate, even after major storm events or prolonged periods of above-average precipitation. Conversely, in areas of high precipitation, infiltrating rainwater or snowmelt may cause acid generation and leaching of copper and other minerals (particularly sulfide minerals that can be oxidized to water-soluble sulfates or multivalent minerals that can be oxidized from a lower-valent water-insoluble state to a higher-valent water-soluble state) to continue for several years.

Data from previous EPA characterization studies (Table 6) indicate the potential acidity (total sulfur content as determined by peroxide oxidation) of spent leach material varies widely (from less than 10 to greater than 10,000 μg CO_3/g material). Although none of the samples analyzed exhibited the characteristic of EP toxicity, several extracts contained slightly elevated concentrations of cadmium, chromium, lead, selenium, and/or silver.[22]

Leaching Solution

The primary constituent of the leaching solution distributed on dumps is the barren aqueous solution discharged from the copper recovery process. Makeup water may be added to replenish the water lost through evaporation and seepage during leaching, and concentrated sulfuric acid may be added to reduce the pH of the leach solution. The copper recovery process leaves many dissolved substances in the barren solution. Although both cementation and solvent extraction are reasonably effective in recovering the copper, the other substances continue to accumulate until their concentration reaches saturation values. The nature of these other substances is directly related to the composition of both the ore body and the type of copper recovery process in use. As a result, generalizations concerning the trace metal composition of the leaching solution, which is considered a process material until such time as it is lost to the environment, are difficult.

In addition to leaching pyrite and other iron-bearing minerals, the cementation process (Equations 18 and 19) results in a buildup of dissolved iron in the leach solution. The typical brown color of the water in barren solution ponds is indicative of low copper content and high iron content. The iron concentration is controlled by precipitation of iron oxides and jarosites within the dump and by the steady-state pH of the system.

The barren solution from the cementation process will also contain most of the original sulfate salts present in the leach liquor. Table 7 presents the results of an analysis of the elemental composition of the barren aqueous solution from a representative leaching operation.[23]

TABLE 6. POTENTIAL ACIDITY AND EP TOXIC CHARACTERISTICS OF SPENT LEACH MATERIAL[a]
(mg/liter except as noted)

Constituent	RCRA hazard criterion	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Potential acidity, μg CO_3/g	NA[b]	10,220	<10	1370	3458	2910	2300	<10	<10
Arsenic	≥5.0	0.0341	<0.0042	<0.0030	0.0205	<0.012	<0.012	<0.0015	<0.0015
Barium	≥100.0	0.019	0.04	0.11	0.12	0.21	0.19	<0.001	0.038
Cadmium	≥1.0	0.049	<0.008	0.012	0.016	<0.008	0.015	0.025	<0.008
Chromium	≥5.0	0.150	<0.001	0.004	0.004	0.009	<0.001	0.073	0.004
Lead	≥5.0	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	0.260	<0.084
Mercury	≥0.2	<0.0008	<0.0008	<0.0002	<0.0002	0.0022	<0.0002	<0.0010	<0.0010
Selenium	≥1.0	0.0594	0.0060	0.0092	0.0356	<0.005	<0.005	<0.0036	<0.0057
Silver	≥5.0	0.041	<0.002	0.006	0.005	<0.002	0.012	0.120	<0.002

[a] Source: Reference 22.

[b] NA = not applicable.

TABLE 7. ELEMENTAL COMPOSITION OF BARREN AQUEOUS SOLUTION FROM CEMENTATION PROCESS[a]

Element		Concentration	Q or S[b]
Aluminum	(Al)	5.90	Q
Arsenic	(As)	<0.01	S
Beryllium	(Be)	0.00008	S
Bismuth	(Bi)	-	S
Calcium	(Ca)	0.4	S
Chromium	(Cr)	-	S
Cobalt	(Co)	0.005-.01	S
Columbium	(Cb)	0.002	S
Copper	(Cu)	0.09	S
Gallium	(Ga)	-	S
Germanium	(Ge)	<0.001	S
Iron	(Fe)	1.-5.	S
Lanthanum	(La)	0.01	S
Lead	(Pb)	0.003	Q
Magnesium	(Mg)	2.52	Q
Manganese	(Mn)	0.35	Q
Molybdenum	(Mo)	<0.001	S
Nickel	(Ni)	0.011	Q
Silicon	(Si)	0.56	Q
Silver[c]	(Ag)	0.05-0.1	S
Sodium	(Na)	0.1	S
Tin	(Sn)	0.0002	S
Titanium	(Ti)	<0.01	Q
Uranium	(U)	0.0087	Q
Vanadium	(V)	<0.002	S
Yttrium	(Y)	0.003	S
Zinc	(Zn)	0.17	Q
Total residue, g/liter		185	-

[a] Source: Reference 23.

[b] Q = quantitative chemical analysis; S = semiquantitative analysis.

[c] Silver reported in ounces per ton, all others in weight-percent.

The constituents of the raffinate from the solvent extraction process depends on the following:

- Type of solvent used
- Type of carrier used (e.g., kerosene)
- Rate at which equilibrium conditions are approached
- Rate and extent to which organic and aqueous phases disengage from the emulsion created during the mixing stage
- Mechanisms designed to remove entrained organics from the raffinate

The organic solvents and carriers currently used for solvent extraction are specifically formulated to have very low solubility for impurity metals.[11] Consequently, these metals remain almost entirely in the raffinate. Contamination of the raffinate by the organic solvent is also minimized, as excessive use of solvents can have a significant impact on the cost of producing copper. Typically, the amount of solvent in the raffinate is estimated to be around 100 ppm. Newer organic solvents (e.g., LIX 84) have been used successfully (for example, at the Tyrone Mine near Silver City, New Mexico) to reduce solvent loss to the raffinate to less than 30 ppm. The raffinate may also contain degradation products of the solvent. No simple analytical method, however, appears to have been found to determine the amount of the organic solvent and carrier materials lost by entrainment and dissolution in the raffinate.[24]

Pregnant Leach Liquor

Dissolution of copper minerals produces copper, ferric and ferrous ions, and sulfuric acid. The amounts of these and other constituents dissolved in the pregnant liquor vary widely with the type of mineralization being leached, the characteristics of the leach solution, and the leaching method used.

The type of copper mineralization affects the rate of leaching and the subsequent copper content of the pregnant leach liquor. Ores and waste rock containing predominantly oxidized copper minerals are more readily leached and give rise to more highly concentrated pregnant liquors than do copper sulfide ores. On the other hand, reduced copper ores containing pyrite (FeS_2) and other base metal sulfides give rise to pregnant solutions with a higher iron content and a lower pH.

The pH of the leaching solution is indicative of bacterial activity and, subsequently, the generation of ferric sulfate, which is the principal factor controlling the rate of dissolution of copper and other metals contained in the host rock and thus their occurrence in the pregnant liquor. As noted above, the oxidation of sulfide minerals, principally pyrite, produces sulfuric acid, which lowers the pH of the leach solution. The pH of pregnant liquors averages around 2.4, but it may range between 1.9 and 3.0.[13] At these low pH's, the solubilities of many toxic metals are increased (arsenic and selenium are exceptions, although they still may be found in significant concentrations in acidic solutions). Figure 7 illustrates the effect of pH reduction on the aqueous solubility of various metals.[10] Data on the concentration of EP toxic metals in several samples of dump and heap leach liquors, which (like the leaching solutions) are considered process materials until such time as they are lost to the environment, are presented in Table 8.[22]

The relative mobilities of the elements in different subsurface environments (oxidizing, acid, neutral-alkaline, reducing) are presented in Table 9.[25] This table indicates the effect of pH and oxidizing/reducing conditions within leach dumps on the leaching potential of copper and other minerals. Other phenomena that may increase the mobility of constituents in the host rock and, consequently, their occurrence in the pregnant liquor include metal complexation and ion pairing.

The leaching method used to extract copper from the ore/waste rock has a significant impact on the characteristics of the pregnant liquor. As noted in Table 3, the copper content of the pregnant solution from vat and agitation operations ranges from 30 to 50 kg/m^3, whereas the copper content of the pregnant solution from dump, heap, and in situ operations is generally less than 5 kg/m^3. This difference is attributable to the relative particle size of the leach material and the efficacy of contact between the leach solution and the host rock. Similar differences in the mineral content of the pregnant liquor may be observed for other minerals for the same reasons. Other aspects of the various leaching methods that determine the characteristics of the

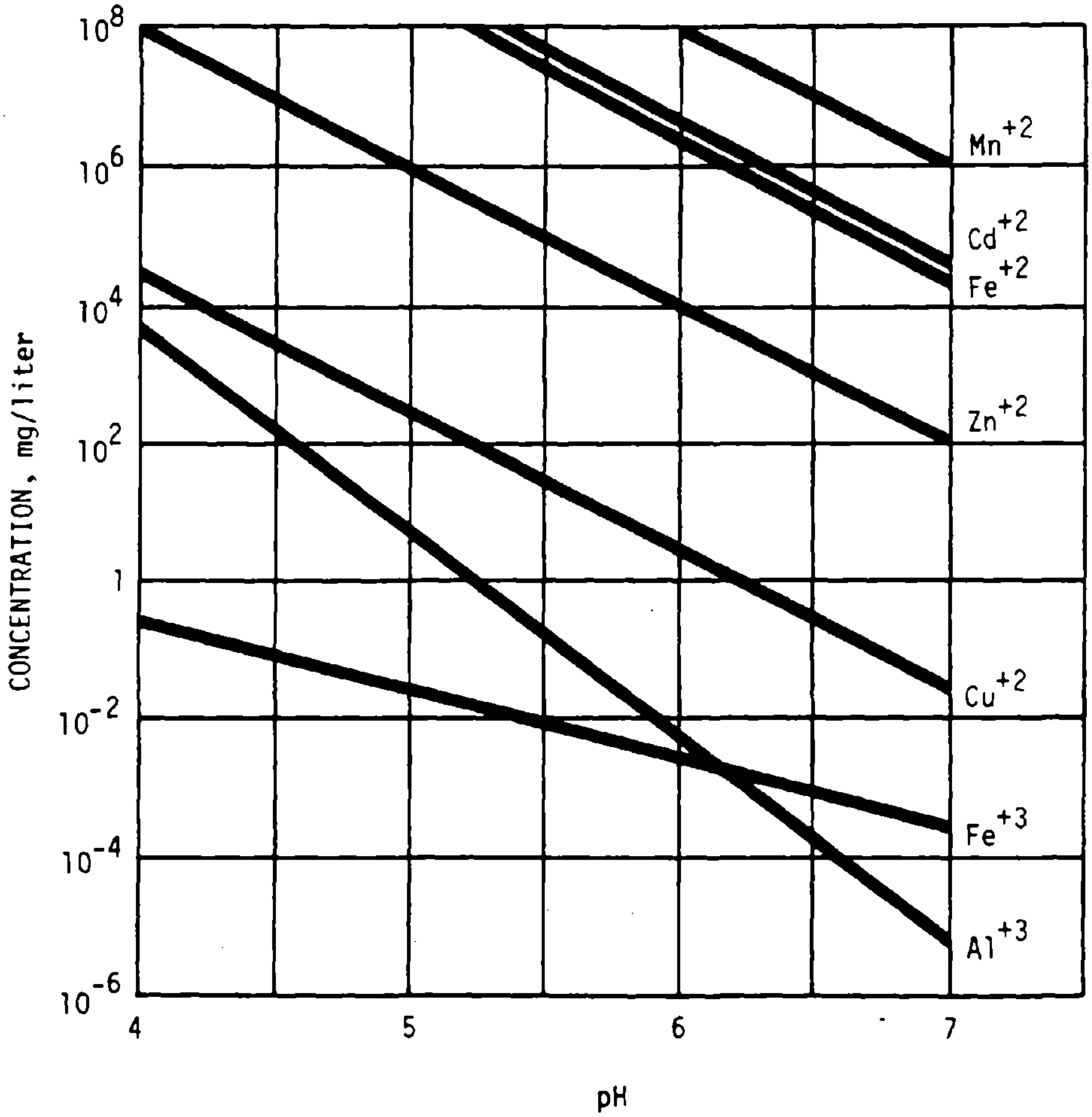

Figure 7. Solubilities of oxides and hydroxides of various metals.

Source: Reference 10.

TABLE 8. CONCENTRATION OF EP TOXIC METALS IN SAMPLES OF PREGNANT LEACH LIQUORS[a] (mg/liter)

Constituent	RCRA hazard criterion	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
pH	≤2 or ≥12.5	1.90	2.60	1.82	1.95	2.49
Arsenic	≥5.0	4.23	2.15	7.8	3.5	2.5
Barium	≥100.0	<0.001	<0.02	<1.0	<1.0	<1.0
Cadmium	≥1.0	1.72	1.40	1.8	0.82	0.55
Chromium	≥5.0	<0.001	0.45	3.4	1.2	0.81
Lead	≥5.0	3.30	<4.20	<0.05	<0.05	<0.05
Mercury	≥0.2	0.001	<0.0002	<0.002	<0.002	<0.002
Selenium	≥1.0	2.74	2.13	0.57	0.35	<0.01
Silver	>5.0	0.22	0.64	<0.05	<0.05	0.13

[a] Source: Reference 22.

TABLE 9. RELATIVE MOBILITIES OF THE ELEMENTS

Relative mobilities	Chemical environment			
	Oxidizing	Acid	Neutral to alkaline	Reducing
Very High	Cl, I, Br S, B	Cl, I, Br S, B	Cl, I, Br S, B Mo, V, U, Sc, Re	Cl, I, Br S, B
High	Mo, V, U, Sc, Re Ca, Na, Mg, F, Sr, Ra Zn	Mo, V, U, Sc, Re Ca, Na, Mg, F, Sr, Ra Zn Cu, Co, Ni, Hg, Ag, Au	Ca, Na, Mg, F, Sr, Ra	Ca, Na, Mg, F, Sr, Ra
Medium	Cu, Co, Ni, Hg, Ag, Au As, Cd	As, Cd	As, Cd	
Low	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Ti	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Ti Fe, Mn	Si, P, K Pb, Li, Rb, Ba, Be Bi, Sb, Ge, Cs, Ti Fe, Mn	Si, P, K Fe, Mn

(continued)

TABLE 9 (continued)

Relative mobilities	Chemical environment: Oxidizing	Acid	Neutral to alkaline	Reducing
Very low to Immobile	Fe, Mn			
	Al, Ti, Sn, Te, W	Al, Ti, Sn, Te, W	Al, Ti, Sn, Te, W	Al, Ti, Sn, Te, W
	Nb, Ta, Pt, Cr, Zr	Nb, Ta, Pt, Cr, Zr	Nb, Ta, Pt, Cr, Zr	Nb, Ta, Pt, Cr, Zr
	Th, Rare Earths	Th, Rare Earths	Th, Rare Earths	Th, Rare Earths
				S, B
				Mo, V, U, Sc, Re
			Zn	Zn
			Cu, Co, Ni, Hg, Ag, Au	Co, Cu, Ni, Hg, Ag, Au
				As, Cd
				Pb, Li, Rb, Ba, Be
				Bi, Sb, Ge, Cs, Ti

[a] Source: Reference 25.

pregnant liquor include temperature and rate of application of the leach solution.

The elemental composition of the pregnant liquor from a typical dump leach operation is presented in Table 10.[23]

GROUND-WATER CONTAMINATION DATA

Chino Lampbright Leaching Area

A study of the ground-water quality at the Lampbright leaching area of Kennecott Corporation's Chino mine was conducted between December 15, 1981, and August 25, 1982.[26] A map of the Chino operations and the Lampbright leaching area is presented in Figure 8. The Lampbright leach area is constructed on an unlined natural drainage basin. Pregnant liquors are collected at the toe of the leach pile in an unlined leachate collection pond. The pregnant liquors are then pumped to a cementation plant for copper recovery. At the time of the study, the Lampbright leach area occupied approximately 500 acres.

Nine parameters identified as potential indicators of seepage from the leach pile [calcium, magnesium, manganese, nickel, zinc, pH, total dissolved solids (TDS), sulfate, and fluoride] were found in one well at levels that indicated an impact from the dump leaching operation. Levels of calcium, TDS, and sulfate indicative of impact were also found to be present in another well. Thus, the study concluded that the leaching operation had an impact on the quality of water in these two wells.

Tyrone No. 2 Leach Dump

Copper leaching operations in New Mexico are subject to the State's Ground-Water Quality Protection Regulations, which require any person who discharges effluent or leachate that may move directly or indirectly into ground water to obtain and operate within the conditions of a permit or "discharge plan." All discharge plans contain monitoring provisions that require the sampling, analysis, and reporting of ground-water and leachate quality.

In accordance with these provisions, the Phelps Dodge Corporation has collected 5 years of ground-water quality data from monitoring wells in and around the dump leach areas at the Tyrone mine. The locations of some of the

TABLE 10. ELEMENTAL COMPOSITION OF PREGNANT LEACH LIQUOR[a]

Element		Concentration	Q or S[b]
Aluminum	(Al)	0.05-0.1	S
Arsenic	(As)	5.90	Q
Beryllium	(Be)	<0.01	S
Bismuth	(Bi)	0.00008	S
Calcium	(Ca)	-	S
Chromium	(Cr)	0.4	S
Cobalt	(Co)	0.002	S
Columbium	(Cb)	0.005-0.01	S
Copper	(Cu)	-	S
Gallium	(Ga)	0.09	S
Germanium	(Ge)	1.-5.	S
Iron	(Fe)	-	S
Lanthanum	(La)	<0.001	S
Lead	(Pb)	0.01	S
Magnesium	(Mg)	2.52	Q
Manganese	(Mn)	0.35	Q
Molybdenum	(Mo)	<0.001	S
Nickel	(Ni)	0.1	S
Silicon	(Si)	0.011	Q
Silver[c]	(Ag)	0.003	Q
Sodium	(Na)	0.56	Q
Tin	(Sn)	0.0002	S
Titanium	(Ti)	<0.01	Q
Uranium	(U)	0.0087	Q
Vanadium	(V)	<0.002	S
Yttrium	(Y)	0.003	S
Zinc	(Zn)	0.17	Q
Total residue, g/liter		185	-

[a] Source: Reference 23.

[b] Q = quantitative chemical analysis; S = semiquantitative analysis.

[c] Silver reported in ounces per ton, all others in weight-percent.

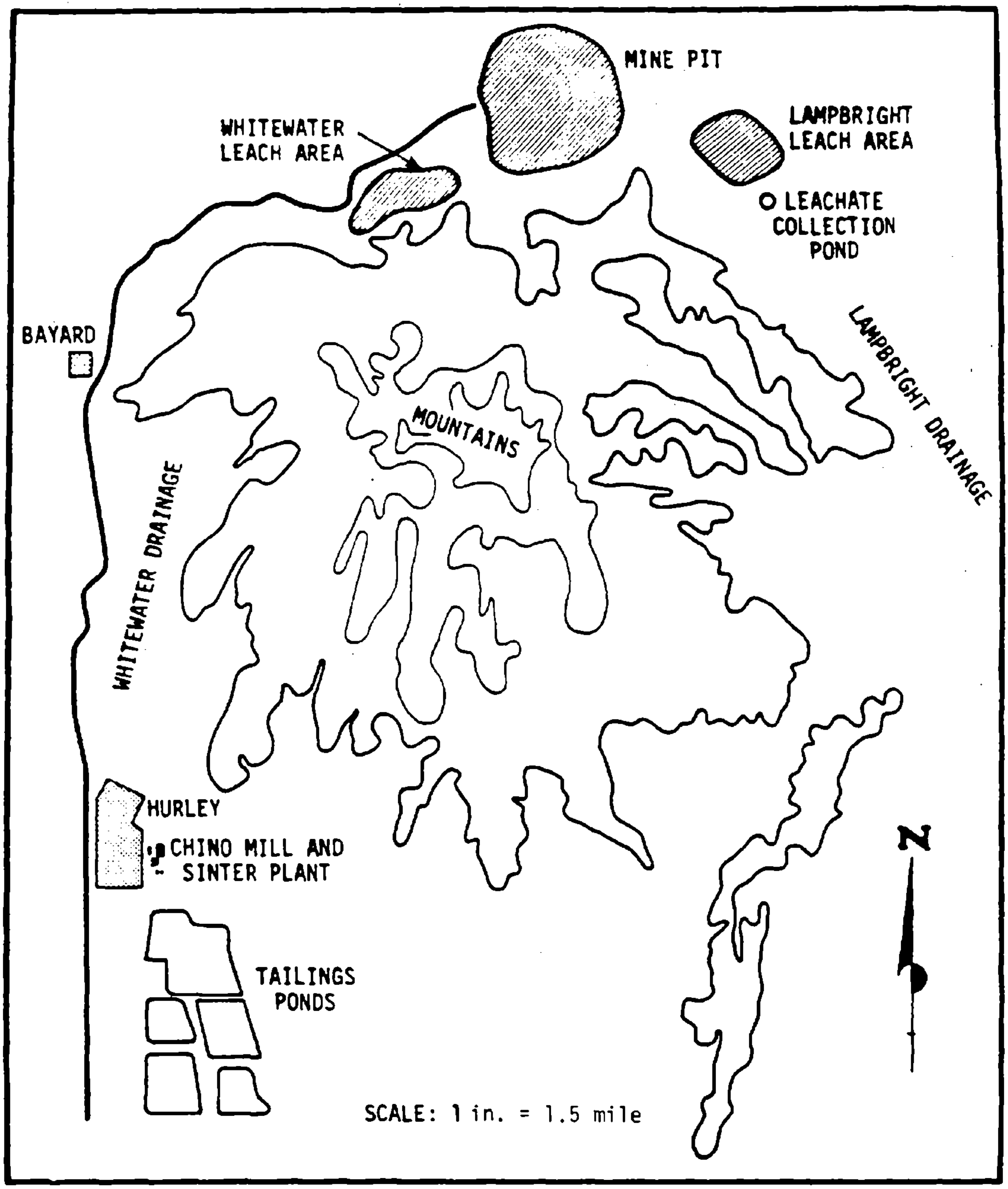

Figure 8. Map of the Chino operations.

Source: Reference 26.

monitoring wells are shown in Figure 9. The data indicate that some contamination of the ground water has occurred in the vicinity of the No. 2 dump, as evidenced by an increase in the concentration of total dissolved solids and dissolved iron and a decrease in the pH in Wells 6-3, 6-4, and 6-5 over background conditions (Well 4-1). These data are presented graphically in Figures 10 through 12.

Globe/Miami Area

The Globe/Miami mining district east of Phoenix, Arizona (Figure 13) was the focus of a recent water quality study by the Central Arizona Association of Governments.[28] The objective of the study was to assess the impact of past and present mining activities on water quality in the Pinto and Pinal Creek drainage basins. The study concluded that surface runoff from past dump leach activities at the Bellview-Gibson mine site has degraded surface-water quality in Pinto Creek; however, ground water in the Pinto Creek basin is generally of high quality. Table 11 presents analytical results from surface runoff and ground-water samples in the Bellview area as well as the appropriate stream standards. The Globe/Miami water quality study also reported that surface and ground water in the Pinal Creek basin have exhibited significant deterioration over the past 40 years but that the exact source(s) of contamination are difficult to identify because of the large number (greater than 200) of active and inactive mining sites in the area (see Figure 14).

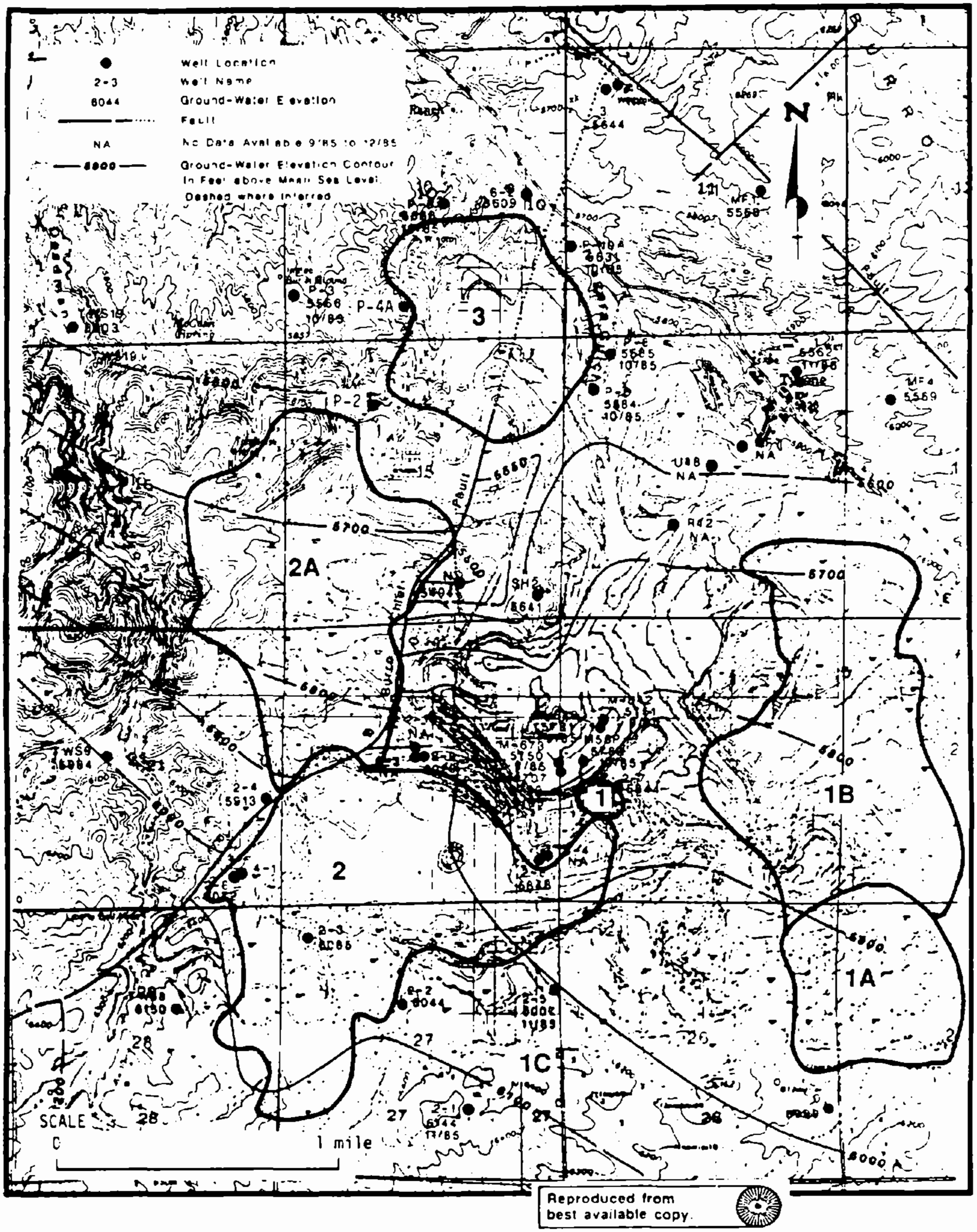

Figure 9. Location of the ground-water monitoring wells in relation to the leach dumps at the Tyrone mine.

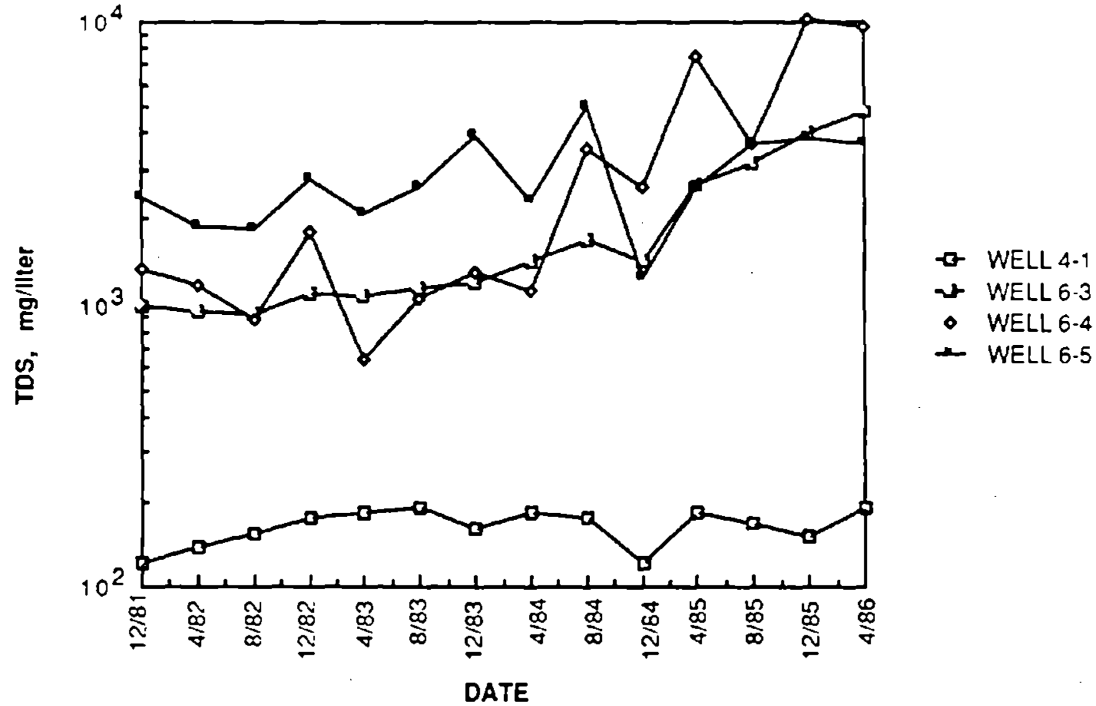

Figure 10. Concentration of total dissolved solids in wells around Tyrone's No. 2 leach dump.

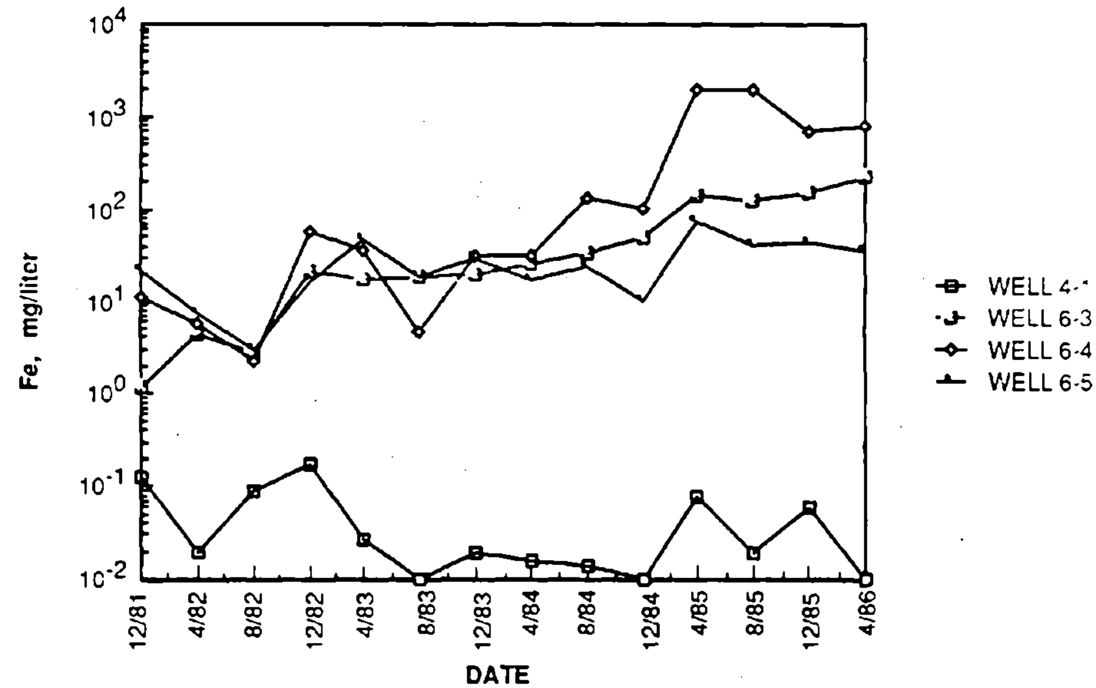

Figure 11. Concentration of dissolved iron in wells around Tyrone's No. 2 leach dump.

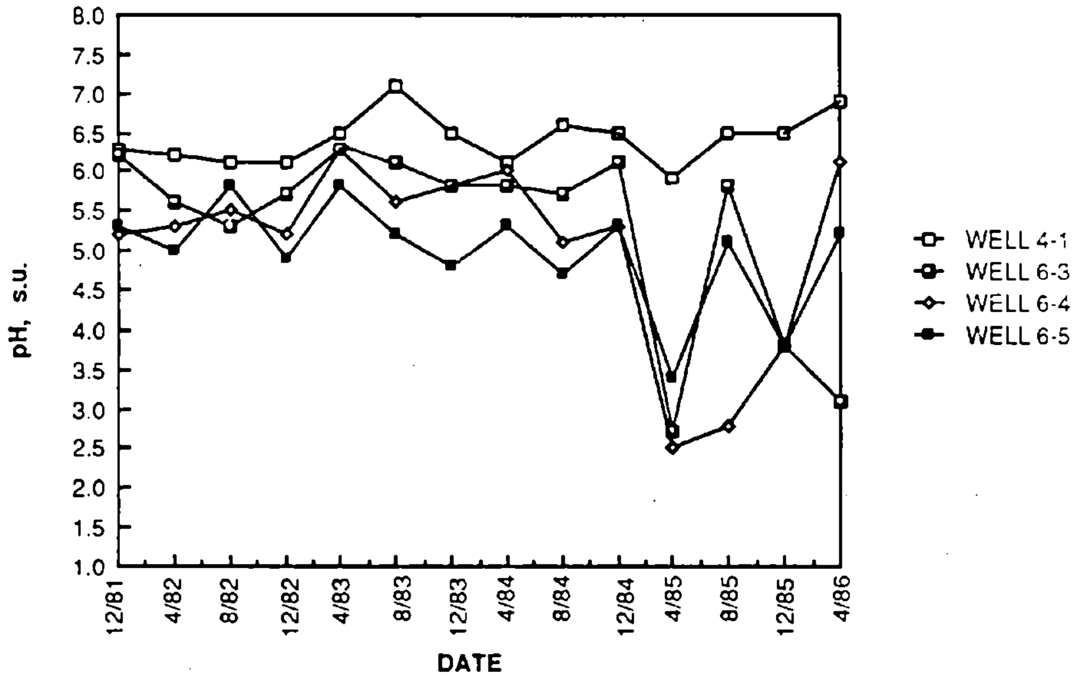

Figure 12. pH level in wells around Tyrone's No. 2 leach dump.

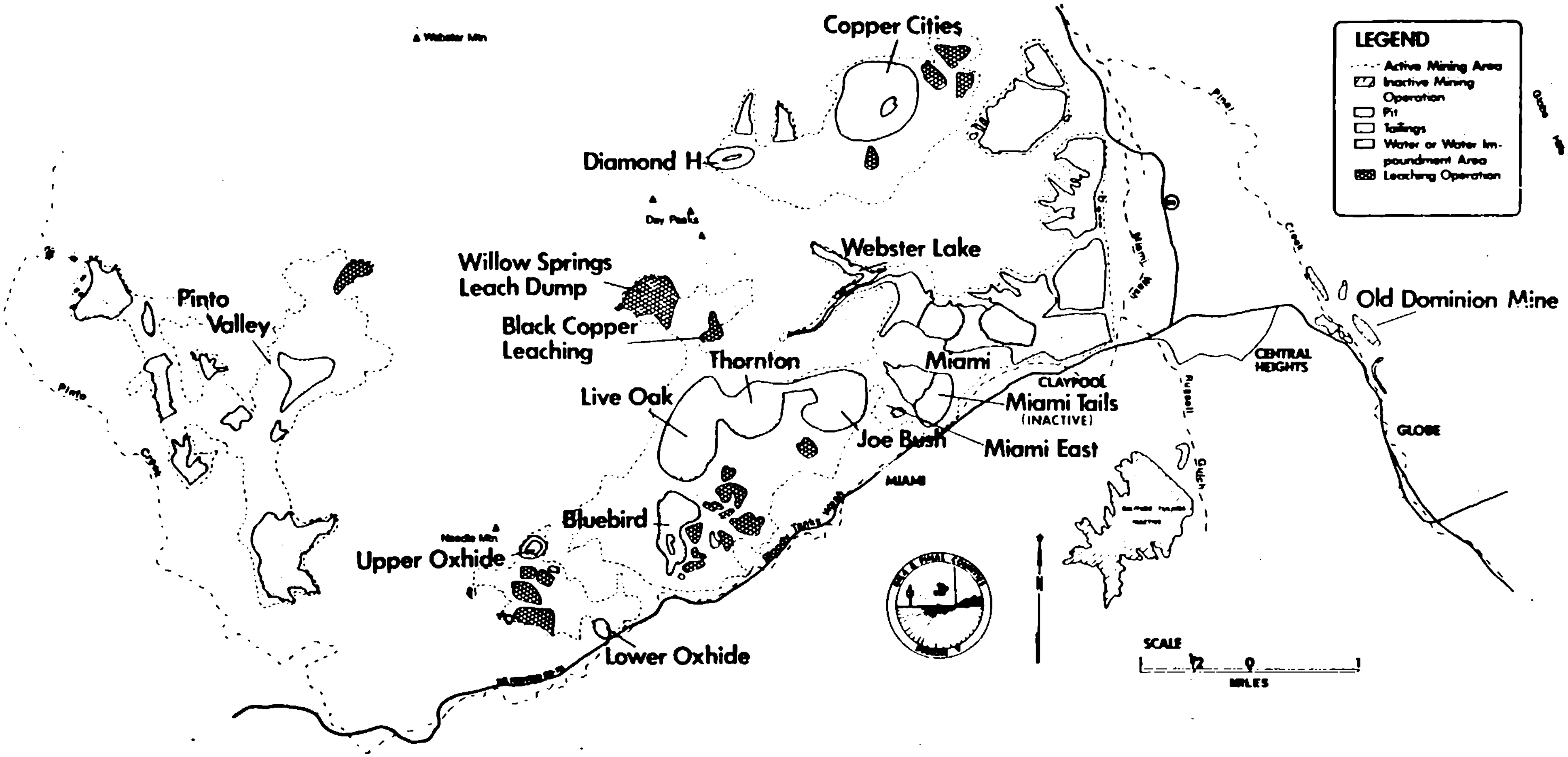

Figure 13. Globe/Miami mining district.

Source: Reference 29.

TABLE 11. COMPARISON OF SURFACE RUNOFF, GROUND WATER, AND ARIZONA STREAM STANDARDS BELLVIEW-GIBSON AREA SAMPLING[a]
(mg/liter except as noted)

Parameter	Mineral	Creek at	Belleview	Pinto Cr. at old Hwy. 60 Bridge	Stream standards	Well No. 1	Well No. 2	Well No. 12	Well No. 12 duplicate
Date	7/21/81	8/10/81	8/10/81	8/10/81	--	3/6/82	3/6/82	3/7/82	3/7/82
Time	2345	1650	1730	Comp.	--	1200	1607	1102	1102
Temp, °C	--	9	9	--	--	16	16.5	13	13
Conductivity, umho/cm²	390	--	420	--	--	2400	1050	1900	1900
pH, S.U.	4.8	4.2	6.3	--	6.5-9.0	6.3	5.8	6.0	6.0
Arsenic	<0.02[b]	<0.02	<0.02	<0.02	0.05	<0.02	<0.02	<0.02	<0.02
Nitrate	1[b]	0.6	0.7	0.6	--	<0.1	0.1	0.2	0.2
Silica	89[b]	0.9	10	24	--	19	51	54	51
Alkalinity	<2[b]	6.7	1.1	26.7	--	276	25	<1	<1
Calcium	53[b]	63	43	15	--	509	171	459	466
Chloride	<2[b]	3	1	5.9	--	23	8	31	31
Copper	36.1[b]	17.2	14.4	0.16	0.05	0.17	8	0.06	0.02
Iron	21[b]	0.8	0.7	0.1	--	12	8	115	117
Magnesium	11[b]	10	7	4	--	131	48	140	137
Manganese	1.7[b]	1.1	0.98	0.16	10	19	9	13	13
Potassium	3.7[b]	2.7	2.1	2.2	--	3	2	2	2
Sodium	1.2[b]	3	1	6	--	52	31	79	82
Sulfate	230[b]	228	330	313	--	1693	725	2172	1760
Solids	1662[c]	152	256	186	--	2824	976	2848	2702
Zinc	0.4[b]	0.2	0.5	0.1	0.5	0.09	0.24	0.12	0.12

[a] Source: Reference 28.

[b] Total sample

[c] Suspended solids.

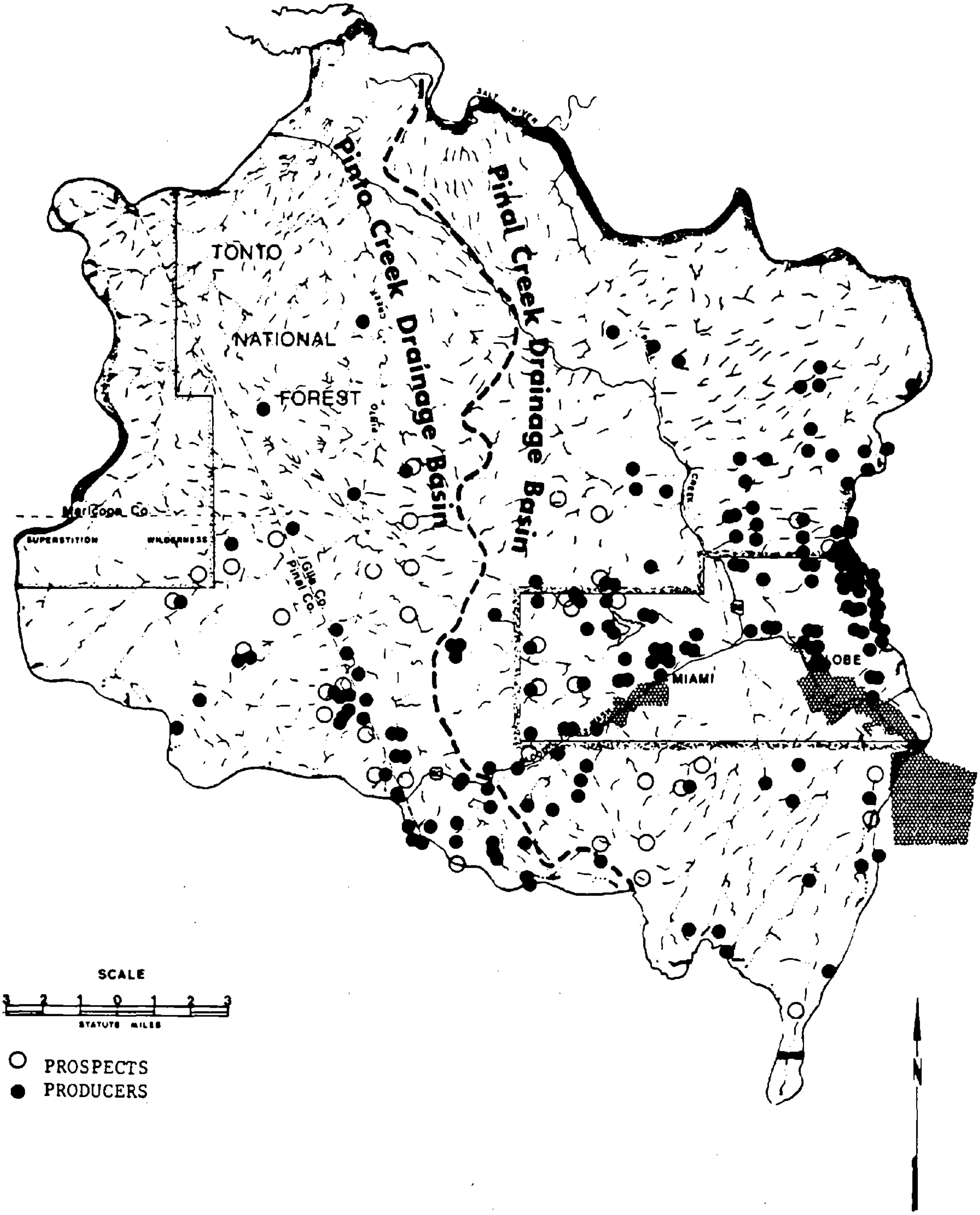

Figure 14. Past and present mining activities in the Globe/Miami area. Source: Reference 27.

SECTION 5

ALTERNATIVE MANAGEMENT PRACTICES

An array of alternative management practices are available for possible implementation at copper dump leaching operations to mitigate actual or potential environmental releases. These practices are capable of addressing a wide range of surface and subsurface conditions associated with active leaching, closure procedures, and the postclosure period. Most leaching operations have adopted a subset of these practices to control leachate production and minimize solution loss. The techniques are controlled by the characteristics of the site and are generally unique.[29] A particular type or combination of management practices is seldom adequate for all leaching operations because of differences in the topography, geology, hydrogeology, meteorology, and detailed operating characteristics of the site. External factors such as the price of copper and the competitiveness of the operation in the world market are also important considerations in determining the economic feasibility of a particular technique. As a result, each leaching operation has implemented a set of management practices that provides the most efficient, cost- effective recovery of copper at that facility. These practices are designed to manage solution losses and monitor fluid balances as an integral part of the leaching operation.

The relevancy of a particular management practice to a specific copper leaching site depends, at least in part, on the operational phase of the site. Three operational phases are distinguished here:

- The active phase includes the development of the site and the period during which copper is being recovered from solution. During this period, new ore may or may not be added to the leach piles. This phase also includes periods during which copper is recovered from liquids that have percolated through the piles, even though the distribution of leaching solutions to the surfaces of the copper heaps or dumps has ceased.

- The closure phase immediately follows the active phase and is the period during which various activities are undertaken to ensure adequate protection of human health and the environment during the post-closure period. During this period, no further additions are made to the leach piles and copper is not recovered from the leachates produced by the piles.

- The post-closure phase, which follows the closure phase, is the period during which the primary activities are the monitoring of the site and the maintenance of the closure technologies implemented during the previous phase.[5]

In addition to these operational management practices, it may be necessary to implement corrective actions to control prior releases or newly discovered releases of contaminants into surface water or ground water. Corrective actions may be required at any point in the operational or closure phases of a copper leaching site. The need for corrective action, however, may not be determined to be necessary until the contamination threatens human health or the environment.

Most of the management practices described in this section can be implemented, to a greater or lesser extent, during any of the operational phases of a copper heap or dump leaching operation. Implementation of some of the practices (e.g., the installation of a liner) is feasible only during the design and initial operating phases. The application of several other technologies is inappropriate during active operations because of the ongoing nature of the material deposition and leaching process. For example, revegetation and capping practices designed to reduce the percolation of liquids and to prevent the flow of air within leach piles are appropriate only at closure. Table 12 lists the various management practices discussed in this section and the operational phases during which they are applied.

During the evaluation of the management practices at copper leaching operations, little information was available as to the effectiveness of these techniques relative to surface-water and ground-water quality directly associated with actual leaching operations. Most mining operations have a variety of potential sources of ground-water contamination, and available information is insufficient for specific determination of the extent, nature, and source of water quality degradation due to the leaching operation. Consequently, implementation of a particular type or combination of management practices

TABLE 12. MANAGEMENT PRACTICES BY OPERATIONAL PHASE

Management practices	Mitigative measures	Active life	Closure	Post-closure	Corrective action
Leachate control systems	Subgrade liners	x			
	Pond and trench liners	x			x
Ground-water management systems	Ground-water monitoring	x	x	x	x
	Ground-water control				x
	Subsurface drains	x	x	x	x
	Subsurface barriers	x	x	x	x
Surface-water management	Diversions	x	x		
	Containment systems	x	x		
Reclamation and closure activities	Revegetation		x	x	x
	Capping		x	x	x
	Security	x	x	x	x

that focuses exclusively on the leaching operation may not effectively address the ground-water contamination problems at the site.

An additional factor in the evaluation of alternative management practices for copper dump leaching operations is the cost of implementation and maintenance. As much real cost data as possible have been obtained from the mining industry sources. In many cases, site-specific characteristics of leaching operations that affect the cost of basic operations also have been identified. Where possible, a range of costs is given to reflect the effect of these variables on the implementation of the management practice.

SITE CHARACTERIZATION AND MONITORING

The implementation of an effective system of mitigative management practices is typically preceded by a preliminary evaluation of the geologic and hydrogeologic characteristics of the copper dump leaching operation. The purpose of this evaluation is to identify conditions in and around the leaching operation that may affect the production of leachates and characterize the pathways for contaminant transport within the surface-water and ground-water systems. The size and complexity of the system of mitigative management practices implemented by a particular site will be based primarily on the information and conclusions drawn from this evaluation. The following subsections discuss the nature and type of information required during this preliminary evaluation and the methods for gathering these data.

Geologic and Hydrogeologic Evaluation

The geologic and hydrogeologic setting of the copper leaching operation is probably the most important factor in determining the need for and design configuration of a mitigative management system. This determination requires the careful collection and evaluation of both regional and site-specific information.

The initial step in the geologic and hydrogeologic evaluation of a copper leaching operation often is a survey of the site's physical and operational characteristics. The information gathered during this survey is used to estimate the potential volume and flow pattern of leachate in and around the copper leaching operation. Components of such a survey include:

- Nature, history, and location of the leaching operation
- Characteristics of the leach material and deposition practices
- Size and location of the leach piles in relation to the existing topography and other mining operations
- Existence of liners or other low-permeability barriers around the leach operation
- Current uses of surface and ground waters in the vicinity of the operations and the proximity of these waters to populated areas.

Any historical precipitation records and existing geologic and topographic maps also should be consulted. Information concerning the characteristics of the material used in copper leaching operations aids in the identification of the nature and amount of leachate produced. The leach material is the principal source of the constituents in the leachate; however, as discussed in Section 4, some contaminants may be introduced by the leaching solution and the recycled liquids from the copper recovery process. The solubility of these contaminants depends, in part, on the mineralization of the ore and the leaching conditions (i.e., pH, Eh, etc.). For example, when exposed to air and moisture, sulfide ores containing high concentrations of pyritic minerals tend to lower the pH of the leachate and increase the solubility of certain heavy metals. The presence of alkaline substances in the leach material or in the surface material surrounding the leach pile, however, may neutralize the acid and reduce metal solubility.[10] The mineralization of the leach material, as well as its physical properties, will also affect the permeability of the leach piles and the extent of contact between the acid solution and the leach material. The weathering and decomposition of certain ores (caused by saturation with acid solutions and exposure to air) result in the formation of fine, clayey materials that tend to plug voids in the rock and restrict both the flow of solutions and the flow of air into the dump.[17]

The size and configuration of a leach pile, including the characteristics of the embankments, are important factors in estimating the volume and flow direction of leachate generated by the pile, as well as the concentration of contaminants. The thickness and cross-sectional area of the leach piles affect the amount of leachate produced, whereas the general configuration of the pile's foundation area and the drainage pattern of the old topography affect the flow patterns of the leachate. This process is complicated by the fact that many copper leach piles cover hundreds of hectares and contain tens of millions of metric tons of low-grade ore. As a result, horizontal and vertical distances between hydraulically upgradient areas and downgradient areas can be great. The variations in the natural conditions over such large distances (thousands of meters) can greatly complicate the hydrogeologic evaluation.

Estimations of the travel rate, direction, and distance of potential contamination from copper heap and dump leaching operations must consider the effect of other mining operations located in the vicinity. Active, inactive, or abandoned mines and/or waste disposal sites may complicate flow patterns when the bottom elevation of underground or open pit mining is below the water table. These mines may act as ground-water sinks, which can control the movement of a plume. Abandoned mine sites and waste rock dumps, particularly those containing a high percentage of sulfide minerals, also may complicate the hydrogeologic evaluation because they represent another potential source of contamination that must be considered.

The volume and characteristics of the leachate will also be affected by the procedures used to place the leach material on the heap or dump site. These procedures affect the relative compaction of various areas of the leach pile. The compression of the leach materials by vehicular traffic and by increasingly greater overburden loads of new leach material may be quite high. In addition, if the ore and gangue material contain carbonates that have the capacity to neutralize sulfuric acid, the deposition of these materials above pyritic materials in the water infiltration pathway can raise the pH of the solution and reduce the potential dissolution of contaminants.

Although a physical survey of the site will provide information on the potential volume and flow patterns of the leachate, monitoring wells are generally used to obtain site-specific data on the geologic and hydrologic characteristics of the site, surface- and ground-water transport mechanisms, and potential human health and environmental receptors. These data will also provide evidence of current environmental damage and water contamination and aid in estimating travel times for contaminants. Often, however, these data will yield only qualitative findings that provide an initial estimate of the impact of copper leaching operations on the surrounding environment. Estimates obtained through simple water balance methods or qualitative transport modeling provide the framework for determining the need and configuration of a more quantitative monitoring program. Preliminary design parameters for monitoring wells can be established through these evaluations, including which water bearing zones to monitor, the approximate number and location of monitoring wells, the parameters to be sampled, the duration and number of sampling events, the location of surface-water sampling points, and the rationale for establishing the monitoring program.

Ground-water Monitoring Program

The obvious objective of a ground-water monitoring program is to detect subsurface releases of leaching solutions and, if necessary, to generate the data required to select and implement a corrective many action strategy. Because ground-water monitoring usually is not practiced at many active copper heap and dump leaching operations, only a limited amount of background information is available from which to determine the leaching operation's contribution to the existing constituents in the ground water. Therefore, ground-water monitoring programs at existing operations will only determine if additional degradation of the ground-water quality is occurring. At new facilities, ground-water monitoring can provide a more accurate measurement of conditions prior to the impact of seepage from the leach piles and collection ponds.

A typical monitoring network consists of a series of nonpumping wells located downgradient from the leach piles and at least one well upgradient in an area that has not been affected by potential contaminant migration.[32] The number of monitoring wells and the complexity of the well network will depend on the size of the copper leaching operation and the presence of other potential sources of contamination in the vicinity. For example, a comprehensive water quality study around several active and abandoned mines in Arizona's Miami/Globe area required a monitoring network composed of 113 new wells. This network included existing water supply wells and wells converted to hydrologic monitoring nests, shallow and small-diameter wells, wells drilled adjacent to deeper existing wells, and deep wells. Kennecott Copper Corporation currently has a monitoring program underway that includes more than 200 wells located in and around the leaching areas.

A comprehensive ground-water monitoring program will initially comprise an array of wells sited according to the information and conclusions drawn from the geologic and hydrogeologic evaluation previously described. If ground-water contamination is detected, however, additional wells may be constructed to gauge the dispersion and attenuation of the leachate. This approach can be a time-consuming and expensive process.[30]

The depth of each well in the monitoring network will depend primarily on the depth and characteristics of the underlying aquifer and the vertical spread of potential contamination.[30] The depth of aquifers under copper leach sites varies considerably, and they are often very deep, particularly in the arid regions of the Southwest. Wells ranging in depth from 30 meters to more than 3000 meters have been required at Kennecott Corporation's Bingham Canyon operation to provide adequate monitoring of ground-water quality.

The size of a monitoring well will depend on the sampling method used, flow rates in the aquifer, and the characteristics of the material surrounding the site of the proposed well. Vacuum and pressure sampling methods that require relatively small holes (51 mm) cannot be used in wells deeper than about 9 meters. Consequently, bailers or submersible pumps are required to withdraw samples from the wells. These generally require a relatively large well diameter (102 mm). Larger-diameter holes also may be required if the well is located in tight materials where recovery is slow or if ground-water flow rates are extremely slow.[30]

Monitoring wells may be installed by a variety of methods. Shallow wells (less than 30 meters) are generally augered, driven, or jetted. For deep wells (greater than 30 meters), rotary drilling, jetting, and cable tooling are generally used.[30] Table 13 briefly describes the application of these methods under various geologic and hydrogeologic conditions.[31]

Cost of Site Characterization and Monitoring

The cost of installing well systems at copper leaching operations will vary greatly from site to site. The primary factors that determine these costs are the size of the leaching operation and the complexity of the local

TABLE 13. METHODS OF WELL INSTALLATION[a]

Method		Applications		
Basic	Variations	Geologic material	Max. well dia., in.	Max. well depth, ft
Hand	Augers	Soft soils without excess sand and water; no boulders	6	20
	Driving points	Soft soils free of boulders	3	30
Boring	Rotary auger bucket	Soft soils without excess boulders	48	90
	Spiral auger	Soft soils without excess sand and water; no boulders	6	90
Jetting	Self-jetting	Soft soils free of boulders	8	50
	Wellpoint/riser unit	Soft soils free of boulders	8	50
	Separate temporary jetting pipe	Soft soils free of boulders	8	100
	Separate permanent jetting pipe	Soft soils free of boulders	8	100

[a]Source: Reference 31.

hydrology. Costs will also be affected by the characteristics of the ground water, the extent of contamination (if any), the availability of supplies and equipment, and local wage rates.

Installation costs include the costs of drilling, well materials, crews, and equipment. The principal parameters that will affect installation costs are:

- Well diameter
- Well depth
- Well components
- Drilling specifications
- Geologic material being drilled
- Sampling requirements
- Site access[30]

Table 14 presents some typical costs for drilling and installing well systems.[31]

TABLE 14. 1986 COSTS FOR DRILLING AND INSTALLING 2- TO 4-INCH-DIAMETER WELLS[a,b]

Drilling method	Cost, $/m
Conventional hydraulic rotary	80-130
Reverse circulation hydraulic roters	110-145
Air rotary	55-80
Auger (hollow stem)	35-70
Cable tool	50-55
Hole puncher (jetting)[c]	130
Self jetting[c]	70
Mobilization	1600-1900

[a] Source: Reference 31 (modified).

[b] Includes drilling, well material, and installation costs.

[c] Includes rental of all necessary equipment, e.g., well points, pumps, and header.

LEACHATE CONTROL SYSTEMS

Leach Pile Surface Preparation and Liners

Leach dumps are built on unprepared existing topography. Generally, the sites continue to add fresh ore to these established dumps and leach them indefinitely. As a result, dump sites frequently cover hundreds of hectares and contain tens of millions of metric tons of low-grade ore. Whereas heap leaching (use of specially constructed pads) is practiced to some extent, it has not been demonstrated that pads (i.e., liners) are applicable to practices covering hundres of hectares and containing millions of tons of ore. The massive size of such practices may result in shear forces that would destroy the integrity of a liner.

Heap leaching has been used in place of dump leaching generally because of high permeability or neutralizing characteristics of the area selected for the operation. Most leach sites are selected to take advantage of existing impermeable surfaces and to utilize the natural slope of ridges and valleys for the collection of pregnant leach solutions. Land having this type of geology and terrain, however, is not always within a reasonable hauling distance from the mining operation. For example, Newmont Mining Corporation investigated several sites on which to locate a new copper oxide ore leaching operation for its San Manuel mine. The nearest site having a reasonably impermeable surface and sloping terrain was about 2 miles from the mine pit, and haulage costs would have made a leaching dump operation at that site uneconomical. Therefore, Newmont evaluated a site within 1/2 mile of the pit. This site was covered with a Gila Conglomerate that was very alkaline. It was estimated that each ton of the Gila Conglomerate would have consumed up to 200 lb of sulfuric acid, which would effectively neutralize the leaching solution and cause copper to precipitate at the base of the pile. The surface was also poorly stratified, and permeability ranged between 10^{-7} to 10^{-2} cm/s. These characteristics would have resulted in excessive solution loss and significantly reduced the efficiency of a dump leach operation. The cost of installing a liner and conducting heap leaching as opposed to dump leaching, however, was determined to be a more cost-effective alternative than the extra haulage costs that would have been incurred if the original site had been selected.

Potential solution loss was also a principal reason for the selection of heap leaching at the Anaconda Company mine in Butte, Montana. At that site, the surface of the area selected for the operation was covered with an alluvial material between 5 and 80 feet deep that had been deposited on a quartz monzonite.

In heap leaching, the installation of a liner is generally accomplished in three phases:

1) Excavation and grading of the proposed leach area

2) Preparation of the supporting subgrade surface

3) Installation of the liner[32]

The techniques used during the excavation and grading phase are fairly typical. The site is first scraped and graded by bulldozers to remove all vegetation and to contour the surface to channel the leaching solution toward one or more collection points. Equipment such as sheepsfoot and vibratory rollers also can be used for further grading and compacting of the surface.

The purpose of the subgrade is to provide a relatively firm and unyielding support for the liner material.[32] The Butte mine selected slag with a particle size of minus 4 cm. The material was spread to a depth of approximately 10 cm and compacted with a vibratory roller. The San Manuel mine used Gila Conglomerate that had been well worked and compacted. Generally, the surface of the subgrade must be finished to create a regular, flat surface, regardless of the type of subgrade material used. Rocks and irregularities with sharp edges must be eliminated, although the required regularity and texture of the surface will depend on the type of liner used.

Liners for new copper heap leach sites can be formed from natural earthen (clay) materials, admixed materials, synthetic materials, or a combination of these. The type of liner used will depend on a variety of site-specific factors, including the existing topography, the surrounding climatic conditions, the geologic structure, and the geohydrologic characteristics.

The Tyrone mine near Silver City, New Mexico, recently installed a clay pad over portions of the surface under its proposed No. 3 leach area. Because of the difficulties associated with the excavation, grading, and compaction of the steep slopes, the installation of pads was limited to surfaces having a slope of less than 5:1. The pad installed covered 59 hectares and consisted of 45 cm of compacted soil built in 15-cm lifts. The soil, which was obtained on site, had a minimum fines content of 12 percent and a moisture content of ±2 percent of the optimum level. Each lift was compacted to 98 percent of its maximum dry density.

The Butte mine installed an asphalt liner. Initially, a coating of asphalt primer was sprayed over the slag subgrade to prepare the surface for the deposition of the asphalt pad. The pad itself consisted of a compacted layer of asphalt 8 cm thick. The surface of the pad was cured with a 0.3-cm layer of sealant.

At the San Manuel mine, a synthetic liner was used to cover an area totaling approximately 34 hectares. The material (60-mil, high-density polyethylene) was chosen partly because of its resistance to the corrosive effects of the pregnant liquor solution and partly because of its tensile strength. In the more critical areas where solutions gather, such as collection ditches, 100-mil material was used. The liner material was received in rectangular sheets measuring approximately 8 m by 60 m and heat-welded together.

Prior to deposition of the heap leach material, the liner is covered with sand or gravel to provide a drainage blanket and to protect the surface of the pad from heavy truck travel and damage from boulders.[32] The Tyrone mine spread 46 cm of soil over the clay liner. The Butte mine spread two layers of cover material prior to the deposition of the leaching ore. The first layer consisted of at least 30 cm of fine mine-run material. This was followed by a 1.5- to 1.8-meter-thick layer of coarse mine-run material. The San Manuel mine installed 0.5 meter of a sand and graded gravel mixture. The gravel was approximately 2.5 to 7.5 cm in size. Coarser gravel was used around the edges of the liner to promote drainage of the pregnant liquor solution.

Pond and Trench Liners

Copper leaching operations typically use ponds to collect the pregnant leach liquors from the heaps or dumps and to hold the barren solution from the copper recovery process prior to recirculating it onto the leach heaps. Several operations also use evaporation ponds to collect and evaporate excess solution in the leaching circuit to prevent surface discharges. These ponds generally measure several hectares in size and, where the topography permits, are built into natural drainage basins. A dam is constructed between the valley walls and across the valley floor to form the pond.

At most of the older copper leaching operations, the collection ponds and trenches through which the solutions flow are unlined. In addition, these areas received little or no surface preparation before leaching operations were initiated. The dams are generally constructed of concrete or rock with clay cores. When feasible, the dams are also grouted into bedrock to minimize subsurface seepage. As a result, the amount of leachate discharged into the ground water around these structures is primarily dependent on the permeability of the underlying surface and the integrity of the dams.

At several leaching operations, liners have been installed in the collection ponds and diversion channels to reduce seepage from the site and to increase the amount of copper recovery. This is particularly true of the raffinate ponds that have been constructed within the last 10 years in conjunction with a solvent-extraction plant. Several facilities have also lined the pregnant liquid collection trenches and ponds. Generally, the trenches have been lined with concrete or a synthetic liner such as polyethylene. The collection ponds are typically lined with gunite, clay, or synthetics.

Cyprus Bagdad, for example, recently replaced its principal, unlined, pregnant-liquor collection pond with a new, lined, collection system. Both the trench and pregnant-liquor collection pond were lined with 100-mil polyethylene. The techniques used to install the liner in the collection trench and pond were similar to those discussed in connection with the lining of leach piles. The area chosen for the trench and pond was first excavated and rough graded. After the excavation and grading were completed, a fill subgrade material was hauled to the site and compacted in layers. After the subgrade material was in place and had been adequately compacted and finished, the liner was installed. The liner was cut and spread by hand in the trench and collection pond areas. The seams were then sealed and tested to ensure their integrity. After the liner had been installed, the pipes were laid on the bottom of the pond and a pumping system was installed to carry the pregnant liquor to the copper-recovery plant.

Cost Analysis of Leachate Control Systems

A variety of factors affect the cost of lining the surface of a proposed leach pile or the trenches and ponds of the solution collection system, including the following:

- Type of material used
- Location of the leaching operation and the associated cost of transporting the lining material to the site
- Size of the leaching operation; the economics of scale will generally lower the unit costs for large projects
- Type and consistency of the surface material at the site
- Installation costs associated with the type of material and the quality control procedures required[32]

The estimated cost of installing several different types of liners is presented in Table 15 These costs do not reflect other system components that should be included with a liner system, such as ground-water monitoring wells and diversion systems for surface runoff. Neither do they reflect the cost of installing a system to divert and hold the leaching solution during construction activities in the ponds and trenches.

TABLE 15. 1986 LINER INSTALLATION COSTS[a]

Liner type	Installed cost, $/m^3$
Soil-bentonite	1.90
Soil-cement (15 cm thick and sealer)	3.30
Asphalt-concrete (10 cm thick, hot mix)	7.30-10.2
Chlorinated polyethylene (CPE)	7.40-12.7
Chlorosulfinated polyethylene (CSPE)	7.40-12.7
High-density polyethylene (HDPE)	
60 mil	8.60
80 mil	9.20-9.70

[a] Source: Reference 32.

GROUND-WATER MANAGEMENT SYSTEMS

Adequate evaluation and management of ground-water contamination at copper leach facilities normally involves either 1) monitoring systems designed to detect and evaluate changes in concentrations of chemical constituents in the ground water (discussed on page 64), or 2) control systems designed to manipulate the ground water to contain or remove contaminants or to adjust ground-water levels to prevent formation of a plume. Ground-water monitoring systems can be used during any phase of a copper heap or dump leaching operation to identify the nature or extent of contamination. Ground-water control systems, on the other hand, are used primarily as corrective action measures and may include pumping systems, subsurface drains, or subsurface barriers, used alone or in combination with each other.

Ground-Water Pumping Systems

Ground-water pumping techniques generally involve one or more of the following options: 1) containment of a plume, 2) removal of a plume after measures have been taken to halt the source of the contamination, and 3) diversion of ground water to prevent clean ground water from flowing through a source of contamination or to prevent contaminated ground water from contacting a drinking water supply.[31]

In a typical ground-water pumping system, extraction wells or a combination of extraction and injection wells are used to reduce or control seepage losses through the foundation of the leach dump and collection ponds. The wells must be located at points that intersect the plumes of contaminated seepage. These types of systems are most effective, however, at sites where the underlying aquifers have high intergranular conductivity. They have also been used with some effectiveness at sites with moderate hydraulic conductivity and sites where movement of the leachate is occurring along fractured or jointed bedrock. Ground-water control systems perform poorly in low-transmissivity aquifers.[31]

The use of extraction wells alone is best suited for situations where the hydraulic gradient is steep and the hydraulic conductivity is high. A combination of extraction and injection wells is frequently used when the hydraulic gradient is relatively flat and hydraulic conductivities are only moderate. The function of the injection wells is to direct contaminants to the extraction wells.[31]

Extraction wells have been effective in altering the direction of ground-water movement around tailings ponds in both the Tucson and Globe/Miami copper mining districts. Experience has indicated, however, that adequate monitoring must be provided in areas such as this to assure that sufficient water is pumped from the wells to offset the recharge from the leaching operation and other potential sources of ground-water contamination.[33]

Leaching solutions appear to be readily transportable, as evidenced by the low-pH ground water found around some dump leaching operations. The movement of this ground water can be extremely slow, however, and flow patterns may be difficult to predict, particularly at sites located on fractured bedrock. Also, the flow of ground water may be diverted or distorted by underground or open pit mining operations in the vicinity of the leaching operation that have been excavated below the water table. A major problem in that type of environment is that it tends to interfere with the normal flow pattern of the potentially contaminated water (i.e., through the fractures) and it does not always reach a monitoring well. Extensive hydrogeologic analysis may be reouired to predict ground-water flow directions.

Four types of wells possibly can be used for ground-water pumping: 1) deep wells, 2) ejector wells, 3) wellpoints, and 4) suction wells. The latter two have much less application. Table 16 summarizes the conditions under which each of these well types is most applicable.[31] Deep wells and ejector wells are used when extraction depths are greater than about 6 meters. Ejector wells generally require less piping and a smaller-diameter casing than deep wells, but they are very inefficient (typically less than 15 percent efficiency) and susceptible to clogging in some environments. Wellpoint and suction well systems are best suited for shallow aquifers where extraction is not required below 6 meters. These systems differ primarily in the size and consequent pumping capacity of the well.[31]

In the selection of the components for any of these systems, the nature of the environment in which they will be operating must be considered. The low-pH leachate recovered from the ground water surrounding copper leaching operations may be particularly corrosive to the casings, screens, pumps, and

TABLE 16. CRITERIA FOR WELL SELECTION[a]

Parameters	Wellpoints	Suction wells	Ejector wells	Deep wells
Hydrology				
Low hydraulic conductivities (e.g., silty or clayey sands)	Good	Poor	Good	Fair to poor
High hydraulic conductivities (e.g., clean sands and gravel)	Good	Good	Poor	Good
Heterogeneous materials (e.g., stratified soils)	Good	Poor	Good	Fair to poor
Proximate recharge	Good	Poor	Good to fair	Poor
Remote recharge	Good	Good	Good	Good
Depth of well	Shallow <20 ft	Shallow <20 ft	Deep >20 ft	Deep >20 ft
Normal spacing	5 - 10 ft	20 - 40 ft	10 - 20 ft	>50 ft
Normal range of capacity (per unit)	0.1 - 25 gpm	50 - 400 gpm	0.1 - 40 gpm	25 - 3000 gpm
Efficiency	Good	Good	Poor	Fair

[a]Source: Reference 31.

other equipment used in their construction. High concentrations of iron or other potential precipitates in the water may tend to clog lines and reduce the efficiency of the system.

Subsurface Drainage Systems

Subsurface drainage systems use some type of buried conduit to collect and convey discharges from the leaching operation. The drains essentially function as a continuous line of extraction wells that channel the collected liquid to a treatment or disposal system. Consequently, subsurface drains can be used to contain or remove a plume.[31]

Drains are generally more cost-effective than pumping systems when depths are shallow, particularly in strata with low or variable hydraulic conductivity. Frequently used where the depth to a low permeable barrier is relatively shallow, the drains are laid above the barrier. This approach can be particularly applicable at copper leaching sites where many of the piles are located over bedrock covered with a thin intervening layer of porous alluvial material through which leaching solution may be seeping. As the depth to the impermeable barrier increases, however, the costs of shoring, dewatering, and excavating the hard rock can make such a drain cost-prohibitive. The practical depth limit is about 25 meters. Subsurface drains are also easier to operate and more reliable than pumping systems. Because water is collected by gravity flow and hydraulic pressure, there are no pumps or other electrical components to fail. Operation and maintenance procedures are relatively simple; however, clogging or breaks in pipes can be very costly and time-consuming to repair.

Another potential disadvantage of subsurface drains at copper leaching sites is the clogging of pipes and drains due to the precipitation of iron, manganese, and other minerals dissolved in the solution. This may be caused by excursions of the leachate pH, the presence of iron-reducing bacteria, or the presence of other minerals that form soluble or insoluble iron complexes. Frequent and potentially expensive cleaning of pipes constricted by these materials would be necessary to maintain the effectiveness of the system.

A subsurface drainage system includes the following major components: a drain channel consisting of a pipe or a gravel bed; an envelope to convey flow from the aquifer to the drain pipe or bed; a filter to prevent fine particles from clogging the system; and wells to collect the flow and to pump the discharge to a treatment or disposal process.[31] The pipe or gravel is laid in a trench that has been excavated and graded to prevent ponding and to minimize potential clogging. Maintaining a dry environment during excavation and placement of the pipe generally requires some type of dewatering system. Some type of wall stabilization also may be required in deep trenches or in relatively unstable soils.

Subsurface Barriers

Vertical subsurface flow barriers can be effective in stopping ground-water drainage or diverting it around a leaching site at depths less than 75 feet. These barriers are particularly effective where inflow occurs only at a few isolated locations.[27] These barriers are installed below ground to contain, capture, or redirect ground-water flow in the vicinity of the site. The most common subsurface barriers are slurry walls and grouting.

Slurry walls provide a relatively inexpensive means of reducing seepage in embankments or foundations.[31] Slurry walls are constructed in a vertical trench that is excavated under a slurry and backfilled with a material having a low permeability. The slurry acts essentially as a drilling fluid for shoring the trench hydraulically to prevent collapse; however, it also forms a filter cake to prevent fluid losses into the surrounding ground. The backfill material commonly consists of concrete, a concrete-bentonite mixture, a bentonite-soil blend, or a hybrid of these.[31]

The most important consideration in designing a slurry wall is the permeability of the completed wall. For control of seepage, the wall is keyed into a low-permeability confining layer beneath the site. The depth and nature of this layer, however, will significantly affect both the cost and effectiveness of the wall.

Where the subsurface barrier is to be installed in rock, grouting is usually selected because excavating or driving through this type of material is difficult.[27] Grouting is a process whereby one of a variety of fluids is injected into crevices and joints in a rock or soil mass to reduce water flow and strengthen the formation. Cement is the most commonly used material for grouting applications; however, clay and chemical polymer grouts also are widely used. Chemical grouts can be used to seal porous materials and cracks that are too small to accept a water-cement grout.

Grout curtains are another type of subsurface barrier created in unconsolidated materials by pressure injection. Grout curtains may be much more expensive than slurry walls, however, and achieving low permeabilities in unconsolidated materials may be difficult as a result of gaps that are left in the curtain because of nonpenetration of the grout.

Whereas grout curtains are used to create subsurface barriers around an operation, rock grouting is used to seal fractures, fissures, and other voids in rock. This technique has been used at copper heap and dump leaching sites primarily to seal fractures, fissures, and other voids in rock around dams to reduce seepage. It has also been used in mines to stabilize and strengthen porous and fissured rock.

The effectiveness of grouting depends on accurately locating the water-bearing voids or zones. Complex ground-water flow in fractured and fissured bedrock (such as may occur under copper heap and leach dump sites) can make rock grouting very difficult. The overall permeability of a grout barrier can be significantly reduced if even minor gaps are left in the barrier. Consequently, a thorough site characterization must be conducted during the hydrogeologic evaluation to determine if a site is groutable and the type of grout that should be used.[31]

Cost Analysis of Ground-Water Management Systems

Many of the same conditions that affect the installation cost of monitoring wells will also affect the cost of ground-water pumping systems. In addition to those costs, however, sites installing pumping systems must also absorb the capital cost of the pumps and accessories as well as the operating costs related to the period and duration of required pumping. Table 17 presents some representative costs for selected pumps and accessories.[31]

A method for estimating the total capital and operating costs for well systems has been developed based on the use of existing hydraulic models.[31] This method has been applied to a number of assumed aquifer and plume characteristics to demonstrate their effect on the cost of well systems. Table 18 summarizes the results of this analysis.[31]

TABLE 17. 1986 COSTS FOR SELECTED PUMPS AND ACCESSORIES[a]

Pump/accessory	Cost, $
Jet pumps	
Shallow well (<7.6 m)	200-490
Deep well (<97.5 m)	240-630
Jets and valves	25-100
Seals	15-40
Foot valves	10-50
Air volume controls	10-30
Submersible pumps	
4-inch pump (depth <274 m)	415-1500
Control box	70-1500
Magnetic starters	160-240
Check valves	15-410
Well seals	20-120
Vacuum pumps	
Diesel motors	13,000-49,000
Electric motors	8,800-34,000

[a]Source: Reference 31 (modified).

TABLE 18. SUMMARY OF SEVEN RECOVERY SYSTEM COST SCENARIOS[a]
(1000's $, 1986)

Aquifer and plume characteristics design parameters	Delineation (C)	Design (C)	Wells/drains (C)	Surface infrastructure (C)	Treatment facility (C)	Wells/drains (O&M)	Treatment (O&M)	Monitoring (O&M)	Total (C)	Total (O&M)
Low flux, high transmissivity (100,000 gal/day/ft)										
(plume width x length x depth, ft)										
(250 x 500 x 25) 2 wells; 2 gpm	81	27-110	16	38	32	16	5.4	10.7	190-275	32
(250 x 500 x 250) 2 wells; 2 gpm	160	27-110	54	38	32	22	5.4	10.7	310-390	38
(2500 x 5000 x 25) 2 wells; 20 gpm	215	27-110	16	160	43	16	5.4	10.7	460-540	32
(2500 x 5000 x 250) 2 wells; 20 gpm	430	27-110	64	160	43	22	5.4	10.7	730-810	38
High flux, low transmissivity (5000 gal/day/ft)										
(250 x 500 x 25) 4 wells; 40 gpm	81	27-110	32	38	54	16	16.1	10.7	230-310	43
(250 x 500 x 250) 4 wells; 40 gpm	160	27-110	12	38	54	22	16.1	10.7	400-480	49
(2500 x 5000 x 250) 4 wells; 400 gpm	430	27-107	14	160	118	49	53.7	10.7	880-960	113

[a] Source: Reference 31 (modified).

C = Capital cost.
O&M = Operating and maintenance cost.

As with other management practices used at copper leaching operations, the costs of installation and materials for subsurface drains can vary widely with site conditions. Installation costs will be affected by the depth of excavation, ground-water flow rates, and the characteristics of the soil or rock in which the drain is to be located. Material costs can include pipes, gravel, pumps, and other accessories. Material and installation unit costs are shown in Table 19.

The costs of a slurry wall will be affected primarily by the type of backfill and, to a lesser extent, by the depth and ease of excavation. Table 20 presents the average cost for soil-bentonite and cement-bentonite slurry walls based on depth and type of material excavated.[31] The higher costs for cement-bentonite walls is due primarily to the cost of Portland cement.

The cost of drilling holes and injecting them with grout is shown in Tables 21 and 22.[31] As shown, the cost of grout will have the most significant impact on the barrier's cost. The difficulty encountered in drilling will also affect the cost. The practical depth limit is about 25 meters.

SURFACE WATER MANAGEMENT SYSTEMS

Diversion Systems

Surface-water diversion systems are generally constructed to prevent uncontaminated offsite runoff and potentially contaminated onsite runoff from mixing. Offsite water is prevented from entering the mine site and causing erosion and flooding. Onsite storm runoff is intercepted for transport to an evaporation pond or a contaminant treatment system. Diversion systems can also help to recover supernatant for recycling.

Combinations of drainage ditches, diversion berms, and collection dams are common methods of controlling surface-water movement at copper heap and dump leaching operations.[27] The selection and cost of a specific type of diversion method or combination of methods at a particular site will depend on the characteristics of that site.

Drainage ditches are the most common diversion technique used at copper leaching sites. Drainage ditches are typically designed to accommodate flows

TABLE 19. 1986 COSTS OF MATERIALS AND INSTALLATION FOR SUBSURFACE DRAINS[a]

Item	Unit cost, $	Remarks
Trench Excavation		
Trencher, ladder-type	470-630	1.5-2.5 m deep; 20-40 cm wide
Backhoe, hydraulic	1.80-2.80/m^3	1.2 m wide trench, damp sandy loam soil, 3.6-6 m deep
Dragline	2.50- 3.80/m^3	27-50 m^3/h capacity
Clamshell	4.10-6.20/m^3	15-27 m^3/h capacity
Wall Stabilization		
Sheet piling	75-80/m	Includes pull and salvage 4.5-12 m excavation
Wooden shoring	60-70/m^2	4.3-6 m excavation
Dewatering		
Sumphole	25-50/m^3	Includes excavation and gravel with 30-60 cm pipe
Opening pumping	350-420/day	5-15 cm diaphragm pump
Submersible centrifugal pump	200-420 each	Bronze without installation; 20-90 gpm
Diaphragm pump	300-1150 each	Cast iron starter and level control, without installation, 2 in. discharge; 40-600 lpm

(continued)

TABLE 19 (continued)

Item	Unit cost, \$	Remarks
Drain Pipe		
PVC perforated underdrain	6.90-18.6/m	30 m length; 10.2-30.5 cm diameter
Corrugated steel or aluminum	14.8-25.6/m	15-25 cm diameter
Porous wall concrete	13.2-28.0/m	15-25 cm diameter
Envelope		
Gravel	11.80-13.50/m^3	
Backfill		
No compaction	1.40/m^3	
Air tamped	1.40/m^3	
Compacted	2.00-2.15/m^3	15-20 cm lifts

[a] Source: Reference 31 (modified).

TABLE 20. 1986 COSTS OF INSTALLING A SLURRY WALL[a]

Medium	Slurry trench, soil-bentonite backfill, $/m²			Unreinforced slurry wall, cement-bentonite backfill, $/m²		
	Depth <9 m	Depth 9-23 m	Depth 23-37 m	Depth <18 m	Depth 18-46 m	Depth >46 m
Soft-medium soil	30-60	65-120	120-150	220-300	300-440	440-1100
Hard soil	65-110	75-150	150-300	370-440	440-580	580-1400
Occasional boulders	65-120	75-120	120-370	300-440	440-580	580-1250
Soft-medium rock, sandstone, shale	95-180	150-300	300-730	730-880	880-1250	1250-2570
Boulder strata	220-370	220-370	730-11,000	440-580	900-1400	1400-3090
Hard rock (granite, gneiss, schist)	-	-	-	1400-2050	2050-2570	2570-3450

[a] Source: Reference 31 (modified).

TABLE 21. 1986 COSTS OF COMMON GROUTS[a]

Grout type	Cost, $\$/m^3$
Portland cement	350
Bentonite	460
Silicate	
20%	460
30%	770
40%	1,000
Epoxy	11,000
Acrylamide	2,400
Urea formaldehyde	2,100

[a]Source: Reference 31 (modified).

TABLE 22. 1986 COSTS FOR GROUND BARRIER IN ROCK[a]

Unit operation	Unit cost, $
Injection hole drilling	45/m
Grout pipe	27/m
Grout injection	$7/m^3$

[a]Source: Reference 31 (modified).

resulting from rainfall events with a frequency of between 2 to 100 years, and they should be constructed to intercept and convey the resulting flows at nonerosive velocities.[29] The failure of such systems often results from insufficient capacity and excessive velocity. When operating improperly, such systems can actually increase seepage. Although wider, shallower ditches are generally used to reduce the potential for erosion, site conditions at most copper leaching sites often necessitate the use of narrower and deeper channels that may require stabilization or frequent retrenching.[31]

Drainage ditches are generally installed during the active phase of the operation; however, they can also be used as part of a comprehensive closure plan. When the dump leaching operation at the Copper Cities mine site was closed in 1982, Pinto Valley Copper Corporation constructed a system of diversion trenches to channel overflows from the leach pile collection sumps into the tailings pond for evaporation. The trench system was designed to handle flows resulting from a 100-year storm event and was lined with riprap to prevent erosion.

Diversion berms are usually constructed to prevent excessive erosion by diverting surface flow and reducing slope length. Because they generally consist of compacted earthen ridges designed to direct water away from an area needing protection, they eliminate the need for excavation. Ideally, berms are constructed of erosion-resistant, low-permeability, clayey materials or waste rock.

Regrading is another relatively inexpensive diversion technique that can be used when suitable cover materials are available on site or close to the mine. This technique is effective, however, only after the termination of active leaching operations at a site. A properly sealed and graded surface will reduce ponding, which will in turn minimize infiltration of precipitation and reduce subsequent differential settling and subsurface leachate formation.[27] Surface grading can also reduce runoff velocities, reduce erosion, and roughen and loosen soils in preparation for revegetation.

Certain disadvantages are associated with grading the surface of a copper leach site. Large quantities of a cover material may be difficult to obtain. Haulage costs may be prohibitive if suitable quantities of cover material cannot be located on or near the mine site. Moreover, periodic regrading and future site maintenance may be necessary to eliminate depressions formed through differential settlement and compaction or to repair slopes that have slumped or eroded. In some cases, regrading may actually increase the permeability of a leach pile by breaking up deposits of iron salts that have precipitated onto the surface of the pile.

Containment Systems

At leach operations, containment systems are used in conjunction with surface-water diversion systems to collect onsite stormwater or dike seepage for the treatment necessary for final disposal of the waste or to prepare the waste for recycling. Secondary containment systems also may be used to intercept offsite runoff during and after major storms and equipment malfunctions to prevent liquids from escaping the primary recirculating leaching system.

Most of the containment systems used at copper heap and dump leaching sites are built in existing valleys or natural drainage basins. A concrete or earthen dike is constructed between the valley walls and across the valley floor to form a holding pond.

A typical secondary containment system has been installed at ASARCO's Silver Bell mine for the pregnant liquor and barren solution collection ponds. This system includes several catchment basins located in a dry wash and enclosed by a dam downgradient from the ponds. These basins were designed to handle liquid flows resulting from a 20-year storm event, and they increased the capacity of each of the holding ponds by a factor of approximately 10.

As is typical of many mitigative systems installed around leaching operations, the construction work was performed by mine personnel and equipment. The vegetation and existing sandy dirt and rock were removed and hauled to a site on the mine property. The sides and bottom of each of the basins were then lined with dirt and clayey material obtained near the mine. The dam was also constructed of earth and grouted to the bedrock on the bottom and sides of the basin.

Cost Analysis of Surface-Water Management Systems

A major portion of the expense incurred in the construction of a surface-water management system is the capital cost of excavation. This cost depends primarily on the type of drainage area and the consequent size of the required diversion and/or containment system.[31] The cost of excavation will also be affected by the soil and rock conditions at the site, the return period of design storms, and the expected velocity of the resulting runoff.

Most mining operations can supply the necessary equipment and personnel for removal and disposal of excavated material. If special equipment must be acquired or a subcontractor must be hired to dispose of this material, the costs will increase significantly. Generally, areas are available at most mining sites where the excavated soil and/or rock can be disposed of. Consequently, the haulage distance and resulting cost of disposal will be minimal.

Fill material is used to line diversion ditches and containment areas and to construct berms and dams. The cost of acquiring, hauling, and placing the fill material will depend on the type and availability of the material used, the amount of fill required, and the topography of the site. Gabions and rock riprap are typically used to stabilize ditches against erosion. Fine-grained soils and clay are used to line containment areas. The cost of such materials will depend on the required thickness and screening, the type of equipment needed, and whether grouting is required.[31]

All cost estimates must be made on a site-specific basis. In an estimate of the cost for the construction of a surface-water management system, the following factors should be considered.

- Source and required amount of fill material
- Type and amount of other material required
- Cost of transportation, installation, and/or placement of the materials
- Cost of stabilization
- Maintenance and repair costs

Table 23 presents typical costs associated with the establishment of surface-water control systems.[31]

RECLAMATION AND CLOSURE SYSTEMS

The use of cover systems is generally considered one of the most effective reclamation and closure activities. The proper installation of such systems at a copper heap or dump leaching operation controls surface-water

TABLE 23. 1986 COSTS FOR ESTABLISHING SURFACE WATER CONTROLS[a]

Operation	Output	Unit cost, $
General excavation		
Front-end loader	35-140 m^3/h	0.80-1.40/m^3
Bulldozer	40-120 m^3/h	1.20-1.10/m^3
Ditch excavation		
0.9 m deep	75-100 m/day	4.78-7.00/m
1.2 m deep	50-70 m/day	6.80-10.20/m
Building embankments; spreading, shaping, compacting		
Material delivered by scraper	-	0.55-1.10/m^3
Material delivered by backdump	-	1.10-1.70/m^3
Ditch stabilization		
Riprap	47 m^3/day	21.7-25.8/m^3
Gunite (with 5-cm mesh, 2.5 cm thick)		
Hauling, spreading of gravel (purchase off site)	790 m^3/day	7.00-8.00/m^3

[a] Source: Reference 33 (modified).

infiltration, promotes proper drainage, and creates an area that is more aesthetically pleasing. Because of the size and construction of the leach pile, lack of suitable cover materials, climatology of the area, and the effect of leachates within the piles, the installation of cover systems may be difficult to accomplish or inappropriate at copper leaching operations, however.

Cover systems generally include some type of capping system overlaid with a material capable of supporting revegetation of the area. The systems are discussed in greater detail in the following subsections.

Capping

Capping a leach dump could reduce the infiltration of onsite surface water. Capping is inappropriate for use at active leaching operations because of the ongoing nature of the disposal process. Capping may be prohibitively expensive to install and maintain at inactive and abandoned sites.

Various site-specific factors influence the design of a cap and the selection of capping materials for a particular application. These include:

- Size and configuration of the operation
- Type of ore and waste rock in the leach pile
- Local climate and hydrogeology
- Local availability and cost of cover materials
- Potential for ground-water contamination

Capping entails the placement of a layer of material composed of natural soils and rock, admixed soils, a synthetic liner, or a combination of these materials over the leach pile. Multilayered caps consisting of a vegetative layer, a drainage layer, and a low permeability layer are the most common.[31] Single-layer caps, however, may be effective in many of the mining areas of the Southwest because the climate is arid to semiarid and the average annual precipitation is less than 50 cm.

Mixing of coarse and fine-grained overburden or crushed waste rock obtained from the mining site is probably the most cost-effective method of creating a stronger and less porous cover material. Chemical stabilizers and cements can be added to relatively small amounts of onsite soils to create stronger and less permeable surface sealants. Soils also may be treated with lime, fly ash, bottom ash, and furnace slag.[31]

The capping of copper leach piles has several disadvantages. For example, the cost of preparing, transporting, and applying adequate capping and drainage materials to a leach pile may be prohibitive. As noted earlier, copper leach piles typically cover hundreds of hectares and are constructed in lifts totaling a hundred meters or more. Adequate sealing of the top surface of these piles requires that an enormous amount of material be hauled to the site, spread, and compacted. Also, because most of the side slopes are inaccessible, a large proportion of the ore and waste rock would remain exposed.

Leach dumps tend to form a natural low-permeability cap as a result of the saturation of the pile with acid solutions and the exposure of the waste rock to air. The dissolution of the copper and other minerals in the ore forms a fine, clayey material on the surface of the dump, which decreases the surface permeability of the pile. In addition, ores having a high percentage of pyrite and other iron-bearing minerals will precipitate iron oxide, which further decreases surface permeability. Some of this iron oxide and clayey material also will be deposited in the rocky layers beneath the surface during the downward percolation of the leaching solution, which plugs voids and prevents liquids from reacting with portions of the pile.

Revegetation

Because widely varying climatological factors and soil conditions affect growing conditions, the level of effort required to revegetate leach areas successfully will also vary. A great deal of work would be required at a Southwestern copper facility where a combination of poor soils (high in salts and sulfides and low in nutrients) and arid climate requiring managers to introduce nonnative plant species, to install irrigation systems, and to provide constant maintenance to develop and maintain vegetative cover. Revegetation also requires extra effort at sites in mountainous terrain, where erosion rates are often high, growing seasons are short, and winters are long and severe.[3]

Most revegetation efforts have been directed at tailings ponds in an effort to preveth blowing dust. For example, Pinto Valley attempted to revegetate the Solitude Tailings Pond near Miami, Arizona, beginning in 1959. These efforts have involved spreading native soil over the top of the 4-hectare tailings pond and planting native plants. The soil was obtained from the surrounding hills to minimize haulage costs. The area surrounding the tailings pond was stripped, and vegetation and the surficial layer of dirt was excavated. A layer of this dirt approximately 25 cm deep was spread over the entire surface of the tailings pond. Available mining equipment was used to remove, haul, and spread the soil. The surface of the tailings pond and the area from which the dirt had been obtained were then seeded with a 10-seed mixture of native plants. The project required approximately 20 months to complete.

Cost Analysis of Reclamation and Closure Systems

The costs of capping and revegetaton measures can vary significantly. Table 24 sets forth typical costs associated with the construction of a cover system.[34] The costs of soil conditioners, fertilizers, and plant species at a typical mining site have been estimated to be approximately $2500/hectare.[27]

TABLE 24. TYPICAL COSTS FOR CAPPING AND REVEGETATION[a]

	Unit cost, $/m³		
Material available on site	Clay	Sand	Soil
Excavation	1.86	1.00	1.17
Loading	1.58	0.84	0.98
Hauling	3.39	3.39	3.39
Spreading and compacting	2.52	0.55	2.52
Material purchased off site			
Purchase	10.9	7.88	13.7
Transportation[b]	7.35	7.35	7.35
Spreading	2.52	c	c

[a] Source: Reference 34.

[b] Transportation approximately 32.2 km.

[c] Included in purchase cost.

OTHER ALTERNATIVE MANAGEMENT PRACTICES

Process Modifications

Sulfuric acid leaching is by far the most economical and commonly used hydrometallurgical process for the extraction of copper. Sulfuric acid is used primarily because it is formed naturally by the oxidation of sulfide minerals. In addition, large quantities of this acid are produced as a byproduct of the copper smelting operation. In 1985, the copper industry produced approximately 729 thousand metric tons of sulfuric acid. Although the market for sulfuric acid has been increasing, most smelting operations produce more than can be conveniently sold, and leaching has become a beneficial means of disposing of the acid. As a result, even though the commercial use of sulfuric acid has been increasing, its average price has remained around 54¢/lb ($1.20/kg). Despite the fact that many of the mining companies have reduced their mining and processing activities because of the low price of copper, leaching operations have remained profitable, in part because of this cheap supply of sulfuric acid.

Various alternative hydrometallurgical processes for the recovery of copper have been investigated. The impetus for most of this research, however, has been the identification and development of technologies that produce less sulfur dioxide to be able to meet air pollution control standards while remaining economically competitive with current pyrometallurgical techniques. Consequently, most of this research has focused on the leaching of concentrates. Very little research has been done to identify techniques for reducing the potential for acid generation and/or ground-water contamination from sulfuric acid leaching.

Ferric chloride has been proposed as a leaching agent for copper concentrates and, less seriously, for low-grade ore. The stoichiometry of the leaching reaction of ferric chloride in copper ore has been found to be:

$$CuFeS_2 + 3FeCl_3 \rightarrow 4FeCl_2 + CuCl + 2S^\circ \qquad \text{(Eq. 20)}$$

As this reaction indicates, sulfur is not substantially oxidized to form sulfates as it is when sulfuric acid is used as the leaching reagent. As a result, the acid generation capacity of the leach pile is greatly reduced. In addition, the rate of dissolution of copper in ferric chloride is much faster than in sulfuric acid. Ferric chloride, however, is considerably more expensive than sulfuric acid, and corrosion problems inherent in this type of reagent have limited its use. Furthermore, the nature and impact of the leach liquor's constituents on the environment have not been investigated.[14]

Another concept that has been proposed is the leaching of native copper with a cupric ammonium carbonate solution. Native copper (which accounts for a very small percentage of the Nation's copper supply) is readily soluble in cupric ammonium carbonate solutions, as shown by the following reaction:

$$Cu^{\circ} + Cu(NH_3)2CO_3 + 2NH_4OH \rightarrow [Cu(NH_3)_2]CO_3 + H_2O \qquad \text{(Eq. 21)}$$

The cuprous solution formed in this reaction is reoxidized by contact with air. Copper is recovered as a mixed oxide by boiling the pregnant solution, and the ammonia is recovered for recycle. Various studies have been conducted to investigate the characteristics and feasibility for extracting copper from native copper in a leaching system. This process has not been used on a commercial scale, however, and its potential impact on the environment is unknown.

Enhancements of the biological activity that occurs naturally in most leach dumps are also being studied. New strains of microorganisms that would selectively attack the copper sulfide components in the leach dumps while leaving the iron-containing minerals relatively unaffected are being discussed. The use of bacteria to convert sulfates in the ore into elemental sulfur rather than sulfuric acid is also being investigated. These systems would considerably reduce the acid generation capacity of copper leach dumps and also produce potentially salable sulfur. These enhancements will require considerable research, however, and their commercial exploitation is many, many years away.

Security Systems

Security systems prevent entry into the mining operations and ban access of animals and unauthorized persons to the leaching ponds. The major objective of installing this type of system is to protect the general public and prevent activities that might damage onsite control systems.[34]

Mining sites currently use a variety of security systems, from simply posting "No Trespassing" signs to a comprehensive system of fences, locked gates, and security guards. Fencing equipped with noise-making devices is generally used to limit access by wildlife. Many of the copper heap and dump leaching operations are located in sparsely populated areas, and the mine operators at these sites do not employ extensive security measures. Typically, these sites just limit access to mine service roads, fence easily accessible routes, and post the mine property.[34]

Water Balances

Solution losses through seepage, runoff, and other release mechanisms may be assessed by maintaining a water balance for the leaching operation. Maintaining a water balance involves a total accounting of water entering the leach system and water leaving the system. Water is introduced directly into the system in the leach solution. It also may enter as precipitation, surface-water runoff, or ground-water infiltration. Water may leave the system through process losses, evaporation, transpiration, seepage, or precipitation of hydrated metal salts (e.g., gypsum, $CaSO_4 \cdot H_2O$).[27] The accuracy of a water balance is limited, however, because the amount of water contained in the dump can only be estimated.

To be effective, a water balance must be kept current to assure the efficient use of water and to identify any potential water losses and treatment requirements. Initially, the development of a water balance will require data from a site characterization and monitoring study. This may entail additional engineering time, instrumentation, and outside consultation. After the initial water balance has been completed, the operating parameters of the leaching system, such as flow volumes and direction, need to be updated and verified by continuous field monitoring. Frequently, the operating expense of these activities will be offset by more efficient management of the systems solutions.

Postclosure Monitoring and Maintenance Activities

After copper leaching operations have ceased, long-term monitoring and maintenance activities will be necessary to identify and limit water quality degradation at the site. These activities may include taking periodic samples from ground-water monitoring wells around the site or the continuation of certain inspection and maintenance activities routinely performed during the active life of the leaching operation. Management practices initiated during the closure period also may require inspection and maintenance to assure their continued integrity and effectiveness.

The purpose of the ground-water monitoring program is to determine the long-term impact of leachates generated at the leach site on the surface and subsurface conditions of the surrounding area. The location of the well sites, the sampling frequency, and the scope of the data analysis should be selected to define contaminant migration and dilution and to evaluate the overall effectiveness of the mitigative systems at the site. Where continuing ground-water impacts are identified, further actions, such as ground-water cleanup, placement of subsurface barriers, or plume treatment, may be required.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The conclusions drawn from the information gathered during the study of copper leaching operations are summarized under four major groupings paralleling the organization of this report.

General Characteristics

1) Although the number of active mines in the United States has decreased in recent years, the percentage of primary copper produced by leaching has increased.

   Low copper prices have resulted in the closing of many mining, milling, and smelting operations. Although many of the leaching operations associated with these sites also have been closed, a significant number are still active because of the relatively low operating costs associated with dump leaching. The result has been an increase in the percentage of copper produced by leaching operations in the United States. Estimates indicate that by 1990 approximately 30 percent of the copper produced in this country will be recovered by some type of leaching process.

2) The areas in which copper leaching is practiced are similar in general characteristics.

   Most of the active U.S. copper dump and heap leaching sites are in the Southwest. The climate in these areas ranges from arid to semiarid. The average annual precipitation is generally less than 50 cm, and the average annual temperature ranges from about 10° to 30°C.

   The topography of these areas varies from gently rolling hills to mountainous terrain. Vegetation is sparse. The active leaching operations in Utah and northern and eastern Arizona tend to be located in more mountainous terrain than those in southern Arizona and western New Mexico. The land surrounding many of the active leaching operations consists primarily of sparsely populated and undisturbed vacant land. Some of the active leaching operations, however, are relatively close to residential and urban areas.

Very little surface water is found near active leaching sites in the Southwest. Ground water, which is the principal source of water at most of these mines, tends to be very deep. In the more mountainous environments, however, the amounts of surface-water runoff and ground water are greater because of winter snow accumulation.

Operating Practices

1) Copper leach dumps typically cover hundreds of hectares, are more than a hundred meters high, and contain millions of metric tons of leach material.

   Copper leach piles as small as 8 hectares (Cyprus Johnson) and as large as 850 hectares (Bingham Canyon) were observed during this study. Estimates indicate that more than 5.5 billion metric tons of leach material now exists in copper leach dumps scattered around the United States and in excess of 40 million metric tons of new material is being added to these dumps annually.

2) Dump leaching and heap leaching are distinguished by the use of liners.

   Dump leaching refers to the leaching of low-grade ore that has been deposited directly on the existing topography. The pregnant leach solution is typically collected in unlined natural drainage basins. In contrast, heap leaching refers to the leaching of ore that has been deposited on specially prepared pads. Lined collection systems are used more frequently in heap leaching.

3) Leaching operations are always constructed in the immediate vicinity of the mine site.

   Leach sites are selected to minimize haulage costs and to utilize the natural drainage patterns of the native terrain for collection of the pregnant liquor solutions.

4) Leaching of copper from massive dumps of sulfide ore is accomplished by bacterial activity and, often, by the addition of sulfuric acid.

   Ferric sulfate, the major lixiviant, forms in the presence of oxygen and bacterial activity. The bacteria generate acid in situ, which provides acid for acid-consuming reactions, including oxygen reduction. Frequently, only makeup water is needed in copper dump operations because the oxidation of the sulfide minerals generates sufficient acid to dissolve the copper and maintain an active bacteria population. More effective leaching reagents have been identified, but they are generally more expensive and their impact on the environment is uncertain.

5) Copper is recovered from pregnant leach liquors either by cementation or by solvent extraction/electrowinning.

These processes remove copper from solution and allow other dissolved substances to accumulate. The recovery process itself may add other substances to the leach solutions. The cementation process uses scrap iron to precipitate copper from the pregnant solution. The iron replaces copper in solution, and this iron-rich solution is subsequently recycled to the top of the leach pile. Upon exposure to the atmosphere, the dissolved iron oxidizes to form insoluble salts, which precipitate on the surface of the pile and restrict the flow of solution.

Solvent extraction uses a complexation mechanism whereby copper is coordinated by an organic compound; the copper is then stripped from the organic phase by a strong acid solution. Kerosene is a common carrier used in most solvent extraction operations, and it may appear in small quantities in the raffinate recirculated to the dump.

Environmental Impact

1) Seepage from leach dumps and solution collection systems is the most significant potential mechanism for the release of contamination into the ground water.

One of the primary criteria in siting leaching operations is proximity to the mine. In dump leach operations, the ground surface is neither lined nor treated in any manner to reduce seepage. Because the leaching solutions are in direct contact with the earth, some continuous solution loss results. Releases can also result from pipe and dam failures, equipment malfunctions, and overflows due to severe storm events.

2) The solutions generated in copper dump and heap leaching operations usually have a lower pH and higher concentrations of metals and total dissolved solids than the natural waters surrounding the site.

Most leach materials, particularly those found in copper dumps, contain pyrites and other naturally occurring metal sulfides that oxidize to generate a low-pH solution when exposed to air and microbial activity. The solvent extraction process also reduces the pH of the solution by ion exchange before it is distributed on the leach dump. Generally, acidic solutions increase the solubility and bioavailability of heavy metals contained in the leach material and rock surrounding the dump.

3) The water quality around several active copper dump leaching operations has been affected by leachates that have seeped into the ground water.

The available ground-water monitoring data indicate that some degradation of the ground water has occurred around several copper dump leaching operations. Some seepage of leachates into the ground beneath copper leach dumps is inevitable. The amount of seepage and its impact depend on site-specific factors.

Management Practices

1) Some active copper leaching operations have implemented management practices that include one or more mitigative measures (e.g., pond and trench liners) designed to minimize solution losses.

   Historically, such management practices were implemented solely for economic reasons (to improve copper recoveries). As the potential for ground-water contamination problems associated with leaching became apparent, these practices were implemented for environmental reasons as well. The measures used at a particular site depend on various site-specific factors, the most significant of which are the geology, hydrogeology, topography, and meteorology of the site. The land use and population density of the area surrounding the operation are also considered, as is the cost of constructing and/or installing each potential mitigative measure.

2) The application and efficiency of standard waste management practices at copper leaching operations are frequently limited by the size and environmental characteristics of the site.

   Copper leaching operations are massive; thus, management practices required for adequate control of potential ground-water contamination from leaching operations also must be on a large scale. The geologic and hydrogeologic evaluation required to design and implement an effective surface-water and ground-water control system will be extremely complex, and the required control systems may cover several hundred hectares. The environment of the site may necessitate a system to divert surface water resulting from the torrential rains periodically experienced in the region, but annual precipitation may not be adequate to sustain revegetation efforts. The size of the leaching operation and its surrounding environment often combine to make both lining and capping economically impractical.

3) The cost of implementing and maintaining an effective system of management practices to minimize solution loss and reduce potential ground-water contamination depends on site-specific factors.

   Traditional management practices tend to be very expensive to implement at copper leaching operations because of the size of the oeprations and the natural characteristics of the site. Nevertheless, most of these practices have been implemented economically at or around one or more leaching operations. Proper planning and design procedures are required to select the most appropriate management practices and to minimize costs.

RECOMMENDATIONS

The conclusions of this study have pointed up the need for additional investigation. The following recommendations indicate the areas where further study would be of value.

1) The potential environmental impact of active and abandoned copper leaching operations on surface and ground waters should be evaluated more extensively.

   Currently available surface-water and ground-water monitoring data from active leaching operations are sparse. Only two of the sites visited during the course of this study (Tyrone and Bingham Canyon) were routinely monitoring ground water. New ground-water protection regulations recently implemented in Arizona (where the majority of the active sites are located) should substantially increase the availability of such data.

   A comprehensive investigation of abandoned copper leaching operations, including site preparation used, also should be conducted to evaluate the environmental impact of these sites. A recent study of water-quality problems in the Globe-Miami mining district in Arizona identified more than 200 active and abandoned mines, but it did not specify the number and size of the leaching operations at these sites. Such determinations are needed for an adequate assessment of the impact of abandoned leaching operations on surface-water and ground-water quality.

2) The design and operating characteristics of in situ leaching operations should be investigated further.

   This method is increasing in prevalence. Commercial operations at the Lakeshore and Miami mines and an experimental operation at San Manuel were toured during this study. This method of leaching significantly reduces operating costs because it eliminates the costs of excavation and haulage of ore. The potential environmental impact of these operations, however, may be greater because the leaching solution is injected directly into the ground. Additional information should be developed concerning the distribution of the solution through the rock, the impact of the local geology and hydrogeology on solution and ground-water flow patterns, and the impact of ore fracturing on the surrounding rock.

3) State ground-water protection programs pertaining to copper leaching operations should be reviewed and evaluated.

   New Mexico, for example, requires each mine to develop a discharge plan for each new leaching area on a site. The regulations generally call for extensive geotechnical, geochemical, and modeling studies of the proposed leach site. All discharge plans also must contain monitoring provisions that require sampling, analysis, and reporting of ground-water and leachate quality. Numerical standards for ground water have also been established. Relatively few regulatory requirements have been imposed on copper leaching operations in the State of Arizona prior to this year. Arizona began implementing an extensive new ground-water protection program in August 1986 that may have a significant impact on both active and inactive leaching operations in that State. Each of these programs should be reviewed, along with those of other States, to evaluate their effectiveness with regard to copper dump and heap leaching operations and to determine the need for additional regulations at the Federal level.

4) State and/or Federal ground-water protection regulations should identify the criteria for determining water-quality degradation as they apply to copper leaching operations. The criteria for determining whether water quality degradation from dump leaching has occurred should be identified and evaluated.

The first criterion for determining degradation of water quality concerns the application of water-quality standards. New Mexico, for example, has established one standard for all ground water, regardless of the mine's location or the nature of water use in the area. Many of the leaching operations in this country, however, are located in relatively sparsely populated areas where ground water is used primarily by the mining operation. Less stringent standards may be more appropriate for such sites.

The second criterion for determining degradation of water quality concerns the point of compliance. If ground-water quality is measured at the property boundary, which may be several miles distant from the site of leaching operations, considerable environmental degradation may occur before the point of compliance is reached. Under such circumstances, effective mitigative measures may be difficult to implement, and an earlier detection system may be required. On the other hand, if ground-water quality is measured at the boundary of the leach pile, there would be no opportunity for natural attenuation processes to take place.

5) The economic impact of additional regulatory controls and guidelines on the copper mining industry should be studied.

In its July 3, 1986, regulatory determination, EPA concluded, in part, that the cost of various alternative management practices must be one of the factors considered in determining its regulatory approach to mining wastes. Most U.S. mining operations are operating at less than full capacity, and employment has declined considerably. Foreign competition and large inventories of refined copper, among other factors, have severely depressed the price of copper. As a result, many mining, milling, and smelting operations have been closed. Although many of the leaching operations have remained active, the imposition of some types of new environmental control measures or management practices could increase production costs and result in additional closures. On the other hand, the cost of some control measures and management practices may be offset by an increase in the amount of solution recovered, and the efficiency of the operation may be improved.

REFERENCES

1. Resource Conservation and Recovery Act of 1976. PL 94-580, October 21, 1976.

2. Amendments to the Resource Conservation and Recovery Act of 1976. PL 96-482, October 21, 1980.

3. U.S. Environmental Protection Agency. Report to Congress: Wastes From the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden From Uranium Mining, and Oil Shale. EPA/530-SW-85-033, December 1985.

4. U.S. Environmental Protection Agency. Regulatory Determination for Wastes From the Extraction and Beneficiation of Ores and Minerals. 51 FR 24496, July 3, 1986.

5. Taylor, J. H., and P. F. Whelan. The Leaching of Cupreous Pyrites and the Precipitation of Copper at Rio Tinto, Spain. Institution of Mining and Metallurgy Bulletin 457, 1942.

6. Fletcher, A. W. Metal Winning From Low-Grade Ore by Bacteria Leaching. Transactions of the Institute of Mining and Metallurgy, Volume 79, December 10, 1970:C247-C252.

7. Catanach, C. B. Development and In Place Leaching of Mountain City Chalcocite Ore Body. In: Extractive Metallurgy of Copper - Hydrometallurgy and Electrowinning, J. C. Yannopoulos and J. C. Agarwal, eds. American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), Port City Press, Baltimore, 1976.

8. Jolly, J. L. W. Copper. In: Mineral Facts and Problems. 1985 Edition. Bureau of Mines, U.S. Department of the Interior, Washington, D.C., 1985.

9. Bureau of Mines. Copper. In: Minerals Yearbook. Volume I. Metals and Minerals. U.S. Department of the Interior, Washington, D.C., 1975-1984.

10. Versar Inc. Quantities of Cyanide-Bearing and Acid-Generating Wastes Generated by the Mining and Beneficiating Industries, and the Potentials for Contaminant Release. Prepared for the U.S. Environmental Protection Agency, Economics Analysis Branch, Office of Solid Waste, under Contract No. 68-02-7090 and Contract No. 68-02-7053, June 1986.

11. Biswas, A. K., and W. G. Davenport, eds. Extractive Metallurgy of Copper. 2nd ed. Pergamon Press, New York, 1980.

12. Hoppe, R., ed. E/MJ Operating Handbook of Mineral Surface Mining and Exploration. McGraw-Hill, Inc., New York, 1978.

13. Sheffer, H. W., and L. G. Evans. Copper Leaching Practices in the Western United States. Bureau of Mines Information Circular 8341, 1968.

14. Malouf, E. E. Leaching as a Mining Tool. In: International Symposium on Hydrometallurgy 1973, D. J. I. Evans and R. S. Shoemaker, eds. AIME, New York, 1973.

15. PEDCo Environmental, Inc. Evaluation of Management Practices for Mine Solid Waste Storage, Disposal and Treatment. Volume II. Environmental Analysis Summary - Case Study Findings, Conclusions, and Implications on Related Mining Districts. Prepared for the U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, under Contract No. 68-03-2900, December 1983.

16. Malouf, E. E., and J. D. Prater. Role of Bacteria in the Alteration of Sulphide Minerals. Journal of Metals, 13(5):353-357, 1961.

17. Bureau of Mines. Evaluation of Mill Tailings Disposal Practices and Potential Dam Stability Problems in Southwestern United States. Volume IV. USBM Contract No. S0110520, December 1974.

18. Schlitt, W. J., ed. Solution Management in Dump Leaching. In: Leaching and Recovering Copper From As-Mined Materials. AIME, New York, 1980.

19. Ahlness, J. K., and M. G. Pojar. In Situ Copper Leaching in the United States: Case Histories of Operations. Bureau of Mines Information Circular 8961, 1983.

20. Williams, R. E. Waste Production and Disposal in Mining, Milling and Metallurgical Industries. Miller Freeman Publications, Inc., San Francisco, 1975.

21. Schlitt, W. J., and K. J. Richards. Chemical Aspects of Copper Cementation in Solution Mining Symposium 1974, F. F. Aplan et. al., eds. AIME, New York, 1974.

22. PEDCo Environmental, Inc. Evaluation of Management Practices for Mine Solid Waste Storage, Disposal, and Treatment. Volume I. Characterization of Mining Industry Wastes. Prepared for the U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, under Contract No. 68-03-2900, November 1983.

23. Armstrong, F. E., et. al. Tritiated Water as a Tracer in the Dump Leaching of Copper. Bureau of Mines Report of Investigations 7510, 1971.

24. Cooper, F. D. Copper Hydrometallurgy. Bureau of Mines Information Circular 8394, 1968.

25. PRC Toups. Environmental Assessment of In Situ Mining. Open File Report 101-1980. Prepared for the Bureau of Mines, U.S. Department of the Interior, Washington, D.C., 1979.

26. PEDCo Environmental, Inc. Site Evaluation: Monitoring of the Lamp Bright Dump Leach Area at the Chino Mine, Near Hurley, New Mexico. Prepared for the U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, under Contract No. 68-03-2900, December 1983.

27. Envirologic Systems, Inc. National Prototype Copper Mining Management Plan. METF 10. Prepared for the Central Arizona Association of Governments, Florence, Arizona, 1983.

28. Envirologic Systems, Inc. Mining Activities and Water Quality Report. METF 7. Prepared for the Central Arizona Association of Governments, Florence, Arizona, 1983.

29. D'Appolonia Consulting Engineers. Alternative Best Management Practices for the Globe-Miami Area. METF 8. Prepared for the Central Arizona Association of Governments, Florence, Arizona, 1983.

30. U.S. Environmental Protection Agency. Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities. Office of Water and Waste Management, SW-611, December 1980.

31. U.S. Environmental Protection Agency. Remedial Action at Waste Disposal Sites (Revised). EPA 625/6-85-006, 1985.

32. U.S. Environmental Protection Agency. Lining of Waste Impoundment and Disposal Facilities. SW-870, Revised March 1983.

33. Pima Association of Governments. Ground-Water Monitoring in the Tucson Copper Mining District. Prepared for the Bureau of Mines, U.S. Department of the Interior, Washington, D.C., July 1983.

34. PEDCo Environmental, Inc. Evaluation of Management Practices for Mine Solid Waste Storage, Disposal, and Treatment. Volume III. Evaluation of the Effectiveness of Waste Management Practices. Prepared for the U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, under Contract No. 68-03-2900, January 1984.

BIBLIOGRAPHY

Aannerud, S. A. 1953. Process for Total Treatment of Copper-Containing Iron Pyrites. U.S. Pat. 2,653,905.

Amenabar, A. 1944. Process of Treating Copper Ores. U.S. Pat. 2,357,990.

Arbiter, N. Oxidized Copper-Part III. 1957. Eng. and Min. J. 158(3):80-85.

Aldrich, H. W., and W. G. Scott. 1929. Leaching Mixed Oxide and Sulfide Copper at Inspiration. Eng. and Min. J. 128:612-619.

Aldrich, H. W., and W. G. Scott. 1933. The Inspiration Leaching Plant. Trans. AIME. 106:650-677.

Anderson, A. E., and F. K. Cameron. 1926. Recovery of Copper by Leaching. Ohio Copper Company of Utah. Trans. AIME. 73:31-57.

Argall, G. O., Jr. 1963. How Leaching Recovers Copper from Waste and Leach Dumps in the Southwest. Mining World. 24:22-27, Oct. 1963; 24:20-24, Nov. 1963.

Auck, Y. T., and M. E. Wadsworth. 1973. Physical and Chemical Factors in Copper Dump Leaching. (Univ. Utah, Salt Lake City, Utah). 200 pp. (Eng.). C.A. 79, 138780s.

Auck, Y. T. and M. E. Wadsworth. 1973. Physical and Chemical Factors in Copper Dump Leaching. Proceedings of Second Int. Symp. Hydrometallurgy, pp. 645-700 (Eng). C.A. 81, 94421k.

Austin, W. W. L. 1914. Leaching Copper Products at the Steptoe Works. Trans. AIME. 49:668-670.

Ballard, J. K. 1968. Methods of Application of Leach Dump Solution at Anaconda's Butte Operation. Paper presented at SME, AIME Fall Meeting, Minneapolis, MN., September 1968.

Batty, J. V., and B.F. Andrew. 1970. Leach-Precipitation-Flotation Studies on Red Bed Copper Ore Using Controlled Atmosphere. Bureau of Mines Report of Investigations 7375.

Beall, J. V. 1965. Southwest Copper - A Position Survey. Min. Eng. 17(10):77-92.

Bell, G. A. 1939. Leaching Practice and Costs at the New Cornelia Mines of the Calumet and Arizona Mining Co., Ajo, Ariz. Bureau of Mines Information Circular 6303.

Bhappe, R. B., et. al. 1968. Theoretical and Practical Studies on Dump Leaching. Paper presented at SME, AIME Fall Meeting, Minneapolis, MN, September 1968.

Blasket, K. S. 1951. Sulfide Copper Ores and Their Poor Relations - The Carbonates. Chem. Eng. Min. Rev. 43:447-451.

Bogart, J. R. 1961. New Leach Plant Ups Bagdad's Copper Production by 67 Percent. Min. World. 23:26-28.

Braithwaite, J. W. 1976. Simulated Deep Solution Mining of Chalcopyrite and Chalcocite. Unpublished PhD Dissertation, University of Utah, Salt Lake City.

Bryce, D. M. 1968. Percolation and Agitation Leaching of an Oxidized Copper Ore. Canadian Min. and Met. Bull. 61:641-645.

Bryner, L. C., and R. Anderson. 1957. Microorganisms in Leaching Sulfide Minerals. Ind. and Eng. Chem. 49:1721-24.

Bryner, L. C., and A. K. Jameson. 1958. Miroorganisms in Leaching Sulfide Minerals. Appl. Microbiol. 6n(4):281-287.

Bryner, L. C., et. al. 1954. Microorganisms in Leaching Sulfide Minerals, Ind. and Eng. Chem. 46:2587-2592.

DeCuyper, J. A. 1963. Bacterial Leaching of Low Grade Copper and Cobalt Ores. Paper presented at annual meeting of AIME, Dallas, TX, February 1963.

DeCuyper, J. A. 1964. Bacterial Leaching of Low Grade Copper and Cobalt Ores. In: Unit Processes in Hydrometallurgy, M. E. Wadsworth and F. T. Davis, eds. pp. 126-142.

Dennis, W. H. 1947. Recovery of Copper by Leaching. Mine and Quarry Eng., 36:140-146.

Duncan, D. W. and C. J. Teather. 1966. Aqueous Leaching of Sulfide Ores With Bacteria and a Surfactant. United States Patent 3,266,889, August 16, assigned to British Columbia Research Council.

Duncan, D. W., et. al. 1964. Leaching of Chalcopyrite With Thiobacillus Ferrooxidans, Effects of Surfactants and Shaking. Appl. Microbiology. 12:122-126.

Eddy, L. 1919. Ammonia Leaching of Copper Ores. Eng. and Min. J. 107(26):1162-1167.

Fletcher, J. B. 1962. In Place Leaching, Miami Mine. Paper presented at Arizona section meeting, Milling Div., AIME, April 6, 1962.

Fletcher, J. B. 1971. In-Place Leaching at Miami Mine, Miami, Arizona. (Miami Copper Oper., Cities Services Co., Miami, Ariz). TRANS. SOC. MINING) ENG. AIME 1971, 250(4), 310-14(Eng). C.A. 76, 36300f.

Floridis, T. P. 1975. Accelerated Ammoniacal Leaching of Copper. (Virginia Polytech. Inst., Blacksburg, Va). METALL. TRANS., B 1975, 6B(1), 198-9 (Eng.). C.A. 82, 158942m.

Fonseca, A. G. 1974. Ammonia-Oxidative Leach of Chalcopyrite. CIM (CAN. INST. MINING MET.) BULL. 1974, 67(747), 105-10 (Eng). C.A. 81, 124547a.

Franz, M. W. 1959. Leach-Precipitation-Flotation Process. J. Metals. 11(6):382-385.

Griswold, G. 1969. Rock Fracturing Techniques for In-Place Leaching. Paper presented at Ninety-eighth Annual Meeting of the AIME, Washington, DC, February 1969.

Groves, R. D., et. al. 1974. Leaching Coarse Native Copper Ore with Dilute Ammonium Carbonate Solution. (Salt Lake City Metall. Res. Cent., U.S. Bureau of Mines, Salt Lake City, Utah). SOLLUTION MIN. SYMP., PROC. 1974, 381-9 (Eng). C.A. 82, 158963u.

Grunig, J. K. 1966. Some Factors of Ore and Solution Chemistry in the Heap Leaching of Cooper Ores. Paper presented at Regional Conference of Pacific Northwest Min. and Met., April 1966.

Guggenheim, M., and J. D. Sullivan. 1930. Acceleration of Extraction of Soluble Copper From Leached Ores. U.S. Bureau of Mines Tech. Paper 472, 1930, 30 pp.

Habashi, F., and R. Dugdale. 1973. Leaching Studies on Chrysocolla. TRANSACTION SME/AIME, 1973, Vol. 254, p. 98.

Hazen, W. C. 1960. Hydrometallurgical Process. U.S. Pat. 2,954,276, Sept. 27, 1960.

Hilliard, R. V., and C. T. Baroch. 1953. Process of Extracting and Recovering Metals by Leaching and Electrolysis. U.S. Pat. 2,655,472, Oct. 13, 1953.

Howard, E. V. 1968. Operational Aspects of Dump Leaching. Paper presented at SME, AIME Fall Meeting, Minneapolis, MN, September 1968.

Hudson, A. W., and G. D. Van Arsdale. 1923. Heap Leaching at Bisbee, Arizona. Trans, AIME. 69:137-154.

Huttl, J. R. 1961. Cement Copper Begins at Bagdad. Eng. and Min. J. 162(6m):86-88.

Jackson, K. J., and J. D. H. Strickland. 1958. The Dissolution of Sulfide Ores in Acid Chlorine Solutions: A Study of the More Common Sulfide Minerals. Trans. AIME, Vol. 212, pp. 373-379.

Jacobi, J. S. 1963. The Recovery of Copper from Dilute Process Streams. Paper presented at Annual Meeting of AIME, Dallas, TX, February 1963.

Johnson, P. H. 1965. Acid-Ferric Sulfate Solutions for Chemical Mining. Min. Eng. 64:64-68.

Johnson, P. H., and R. B. Bhappu. Chemical Mining - A Study of Leaching Agents. Cir. 99, New Mexico Bureau of Mines and Mineral Resources.

Jones, D. L. 1974. Leaching of Chalcopyrite. (Univ. British Columbia, Vancouver, B.C.). 1974. No pp. Given (Eng.) Avail. Natl Library; Canada, Ottawa, Ont. from DISS. ABSTR. INT. B 1975, 35(11), 5454. C.A. 83, 83039g.

Keller, C. H. 1945. Recovery of Copper from Copper-Bearing Solutions. U.S. Pat. 2,390,540, Dec. 11, 1945.

Kenny, H. C., and H. A. Abramson. Ammoniacal Leaching Process. U.S. Pat.

Keyes, H. E. 1949. Can Leaching Aid the Copper Mines? J. Metals. 1(12):29-31.

Krivsky, W. A., et. al. 1970. Recovering High-Grade Copper from Lean Oxide Ore by Leaching and Cementation. (Continental Copper and Steel Industries, Inc.) U.S. 3,490,899 (Cl, 75-109; C 22b), 20 Jan 1970, Appl. 18 Oct. 1966; 4 pp. C.A. 72, 69596c.

Laist, F., and H. W. Aldrich. 1914. Experimental Leaching at Anaconda. Trans. AIME. 49:671-690.

Lyle, A. G. 1951. Production of Copper Sulfate From Mine Water Precipitate. Can. Min. Met. Bull. 475, pp. 715-716.

Madsen, B. W., et. al. 1975. Application of a Mixed Kinetics Model to the Leaching of Low Grade Copper Sulfide Ores. (Salt Lake City Metall. Res. Cent., U.S. Bureau of Mines, Salt Lake City, Utah). TRANS. SOC. MIN. ENG. AIME 1975, 258(1), 69-74 (Eng.). C.A. 83, 13886g.

Madsen, B. W. 1975. Using Oxygen to Reactivate a Nearly Dormant Copper Sulfide Leach. U.S. Bureau of Mines, R.I. 8056, 9 pp.

Madsen, B. W., et. al. 1975. Prompt Copper Recovery from Mine Strip Waste. U.S. Bureau of Mines, RI 8012, 19 pp.

Maloul, E. E. 1972. Current Copper Leaching Practices. MINING ENGINEERING, August 1972, p. 58.

Marcontonio, P. J. 1976. Chalcocite Dissolution in Acidic Ferric Sulfate Solutions. Unpublished PhD Dissertation, University of Utah, Salt Lake City.

McArthur, J. A., and C. Leaphart. 1961. Leaching of Chuquicamata Oxide Copper Ores, in Extractive Metallurgy of Copper, Nickel and Cobalkt, Queneau, P., Editor, AIME, Interscience Publishers, New York. pp. 347-361.

McElroy, R. O., and D. W. Duncan. 1974. Copper Extraction by Rapid Bacteriological Process. (British Columbia Research Council) U.S. 3,856,913 (CI. 423-27 Boldf. Bulg), 24 Dec 1974, Appl. 290,950, 21 Sept 1972; 6 pp. C.A. 82, 174058H.

Miller, A. 1967. Heap Leaching of Copper Ore at Ranchers Bluebird Mine, Miami, Ariz. Paper presented at SME, AIME Fall Meeting, Las Vegas, Nevada, September 1967.

Milner, E. F. G., et. al. 1974. Copper Hydrometallurgy. U.S. 3,798,026 (Cl. 75/104; C 22b), 19 Mar 1974, Appl. 238,460 27 Mar 1972, 11 pp. C.A. 81, 94451v.

Mishra, R. K. 1973. Low Temperature Surface Reaction in Leachin of Chalcopyrite and Pyrite. (Univ. Utah, Salt Lake City, Utah), 1973, 199 pp. (Eng). C.A. 81, 94352p.

Mitchell, D. W. 1966. Study of Precipitation of Copper on Iron From Acid Solutions. New Mexico State Bureau of Mines and Min. Res., Circ. 86, 1966, 5 pp.

Monninger, F. M. 1963. Precipitation of Copper on Iron. Min. Cong. J. 49:48-51.

Morese, H. W. and H. A. Tobelmann. 1916. Leaching Tests at New Cornelia. Trans, AIME, Vol. 55, pp. 830-855.

Moss, J. F., and J. E. Anderson. 1968. Effects of Environment on Bacterial Leaching Rates. Australasian Inst. Min. and Met. Proceedings, No. 225, March 1968m ,op 15-25.

Nadkarni, R. M., et. al. 1966. A Kinetic Study of Copper Precipitation on Iron - Part I. Paper presented at Annual Meeting of AIME, New York, February 1966. 17 pp.

O'Leary, V. D. 1966. Clarification and Treatment of Mine Drainage Water Prior to Use for Dump Leaching in Butte. Paper presented at Annual Meeting of AIME, New York, February, 1966. 13 pp.

Parker, G. W. 1966. Leach Dump Operation in Butte, Montana. Paper presented at Regional Conference of Pacific Northwest Min. and met., April 1966. 7 pp.

Pemsler, J. P. 1975. Recovery of Copper from Chalocopyrite. (Kennecott Copper Corp.) U.S. 3,880,650 (CI. 75-72; C22b), 29 Apr 1975, Appl. 437-237, 28 Jan 1974; 9 pp. C.A. 83, 208641f.

Power, K. L. 1963. Copper Leaching at ASARCO's Silver Bell Unit, Arizona. Paper presented at Annual Meeting of AIME, Dallas, TX, February 1963. 27 pp.

Razzell, W. E. 1962. Bacterial Leaching of Metallic Sulfides. Can. Min. and Met. Bull., v. 55, No. 599 March 1962, pp. 190-191. Also in Transactions Can. Inst. of Min. and Met. v. 65, pp. 135-136 (1962).

Razzell, W. E., and Trussell. 1963. Microbiological Leaching of Metallic Sulfides. Appl. Microbiol. 11:105-110.

Ricketts, L. D. 1915. Some Problems in Copper Leaching. Trans. AIME, Vol. 52, pp. 737-764.

Roberts, E. S. 1953. Precipitation of Pure Metallic Copper from Copper Bearing Solutions. U.S. Pat. 2,647,825, Aug. 4, 1953.

Schlecten, A. W., and J. L. Bruce. 1952. New Acid-Leaching Section Raises Cyprus Copper Recovery by 10%. Eng. and Min. J. 153(12):88-91.

Shiga, S. Leaching Copper. 1974. (Furukawa Electric Co., Ltd.) JAPAN. 7411,534 (Cl.C22b). 18 Mar 1974, Appl. 7096,692, 02 Nov 1970; 6 pp. C.A. 82, 101512s.

Shoemaker, R. S. and R. M. Darrah. 1968. Economics of Heap Leaching. Paper presented at SME, AIME Fall meeting, Minneapolis, MN, September 1968.

Silo, R. S. 1965. A New Process for Oxidized Ore of Copper by Leaching. Paper presented at Annual Meeting of AIME Chicago, IL, February 1965.

Soto, R. and J. Goldfarb. 1974. Reaction Between Cupric and Sulphide Ions in Solution and the Sulphidization Process. C267. TRANS. INSTN. MIN. METALL. 83, Dec., 1974.

Spedden, H. R., and E. E. Malouf. 1972. Cyclic Leach-Precipitation Process for Recovering Copper Values From Bodies of Ore Material Containing Copper Minerals. (Kennecott Copper Corp.) U.S. 3,661,563 (CI. 75/101R; C 22b), 09 May 1972, Appl. 55,578, 16 Jul 1970; 3 pp. c.a. 77, 37738n.

Stanczyk, M. H. and C. Rampacek. 1963. Oxidation Leaching of Copper Sulfides in Acidic Pulps at Elevated Temperatures and Pressures. U.S. Bureau of Mines Rept. of Inv. 6193.

Stephens, J. D. and J. Savern. 1969. Migration of Leach Solutions Into Mine Waste Rock. Paper presented at Nine-eighth Annual Meeting of AIME, Washington, DC, February 1969.

Sullivan, J. D. 1933. Chemical and Physical Features of Copper Leaching. Trans. AIME, Vol. 106. pp. 515-546.

Sullivan, J. D. 1931. Factors Involved in the Heap Leaching of Copper Ores. U.S. Bureau of Mines Inf. Circ. 6425.

Sullivan, J. D. 1931. Factors Involved in the Heap Leaching of Copper Ores. U.S. Bureau of Mines Rept. of Inv. 3073.

Sullivan, J. D., and G. L. Oldright. Leaching Oxidized Copper ores: Effect of Strength of Acid in Leaching Solvent. U.S. Bureau of Mines Rept. of Inv. 3106.

Sullivan, J. D. and E. O. Ostrea, 1931. Factors Governing the Entry of Solutions into Ores During Leaching. U.S. Bureau of Mines Tech. Paper 498

Sullivan, J. D., and A.J. Sweet. 1929. Factors Governing Removal of Soluble Copper From Leached Ores. U.S. Bureau of Mines Tech. Paper 453.

Sullivan, J. D., and A. P. Towne. 1961. Agglomeration and Leaching of Slimes and Other Finely Divided Ores. U.S. Bureau of Mines Bull. 329, 1930, 60 pp.

Sutton, J.A., and J.D. Corrick. 1961. Bacteria in Mining and Metallurgy: Leaching Selected Ores and Minerals. Experiments with Thiobacillus Thiooxidants. U.S. Bureau of Mines Rept. of Inv. 5839.

Sullivan, J. D., et. al. 1929. Factors Governing the Entry of Solutions Into ores During Leaching. U.S. Bureau of Mines Tech. Paper 441.

Theys, L. 1970. Forty Years of Progress in the Hydrometallurgy and Electrowinning of Copper The Experience of Union Miniere. C.I.M. Bull. 63, pp. 339-351.

Thomas, R. W. 1938. Leaching Copper from Worked-Out Areas of the Ray Mines Arizona. Min. and Met., Vol. 19, pp. 481-485.

Tobelmann, H. A. and J. A. Potter. 1919. First Year of Leaching by the New Cornelia Copper o. Trans, AIME, Vol. 60, pp 22-77.

Toll, R. W. 1947. Copper Recovery From Low-Grade Waters. Min. Mag. 77:83-84.

Ugarte, G. 1974. Leaching of Copper Minerals. (Chile). MINERALES, 29(128):14-23 (Span). C.A. 83, 13867b.

Ugarte, G. 1973. Leaching of Copper Sulfides. Challenging Route to Copper Pyrometallurgy. (Dep. Mines, Univ. Chile, Santiago, Chile). FUTURE COPPER PYROMETALL., PROC. SYM. 1973 (Pub. 1974), 233-72 (Eng.), C.A. 82, 127841y.

U.S. Bureau of Mines. 1961. Bacteria in Mining and Metallurgy: Leaching Selected Ores and Minerals. U.S. Bureau of Mines, RI 5839.

U.S. Bureau of Mines. 1964. Leaching Copper Sulfide Minerals With Selected Autotrophic Bacteria. TI 6423.

Walsh, C. L. and B. A. Adams. 1950. An Improved Process for the Recovery of Metal Ions From Solutions. British Pat. 641,918, Aug. 23, 1950.

Warren, I. G., et. al. 1968. Pretreatment and Leaching of Chalcopyrite. Candadian Min. and Met. Bull, Vol. 61, pp 637-640.

Wartman, F. S., and A. H. Roberson. 1944. Precipitation of Copper From Acid Mine Water. U.S. Bureau of Mines Rept. of Inv. 3746.

Weed, R. C. 1956. Cananea's Program for Leaching in Place. Min. Eng., Vol. 8, pp. 721-723.

Weston, D. 1974. Recovery of Copper Values by Sulfuric Acid Leaching. S. AFRICAN '74 00,517 (Cl.C22b), 30 Oct 1974, Appl. 74 517, 24 Jan 1974; 11 pp. C.A. 83, 101297w.

Woodcock, J. T. 1967. Copper Waste Dump Leaching. In: Proceedings of Australasian Inst. Min. and Met. No. 224, pp 47-66.

Yu, P. H., et. al. 1973. Kinetic Study of the Leaching of Chalcopyrite at Elevated Temperature. INT. SYMP. HYDROMETALLURGY, 2ND 1973 (Pub. 1973), 375-402 (Eng). C.A. 81, 80891b.

Yurko, W. J. 1966. Refining Copper by Acid Leaching and Hydro Metallurgy. Chem. Eng. 73(18):64-66.

Zimmerley, S. R., et. al. 1968. Cyclic Leaching Process Employing Iron Oxidizing Bacterial. U.S.P. 2,829,964, April 8, 1968. (to Kennecott Copper Corp.)

Acid Leaching of Oxidized Copper Ores by Downward Percolation. 1960. U.S. Bureau of Mines Rept. of Inv. 5629.

Chemistry of Leaching Bornite. 1931. U.S. Bureau of Mines Tech. Paper 486.

Chemistry of Leaching Chalcocite. 1930. U.S. Bureau of Mines Tech. Paper 473.

Chemistry of Leaching Covellite. 1930. U.S. Bureau of Mines Tech. Paper 487.

Economics Provide Motive for Growth of Bacteria Leaching. 1966. Eng. Mining Hour., Vol. 167.

Flotation and Leaching at Kennecott. 1928. Eng. and Min. J. 126(26):1008-1015.

How Bacteria Leaches Low-Grade Ores. 1958. Eng. Mining Hour. 159(6):89-91.

How New Leach-Float Plant Handles Greater Butte's Ore. 1953. Eng. and Min. J. 154(6):90-93.

Innovations in Copper Leaching Employing Ferric Sulfate-Sulfuric Acid. 1930. U.S. Bureau of Mines Bull. 321.

Leaching Copper Ores: Advantages of Wet Charging. 1930. U.S. Bureau of Mines Rept. of Inv. 3050.

Leaching Copper Sulfide Minerals with Selected Autotrophic Bacteria. 1964. U.S. Bureau of Mines Rept. of Inv. 6423.

Leaching Mixed Copper Ores with Ferric Sulfate; Inspiration Copper Company. 1926. Trans, AIME, Vol. 73, pp. 58-83.

Method of Leaching Copper Sulfide Material with Ammoniacal Leach Solution. 1955. U.S. Pat. 2,727,818, Dec. 20, 1955.

Microbial Leaching of Copper Minerals. 1963. Min. Eng. 15(6):37-40.

New Technology of Leaching Waste Dumps. 1962. Min. Cong. Journal. 48(11):82-85.

APPENDIX A

TRIP REPORTS

TRIP REPORT
CYPRUS BAGDAD MINING COMPANY

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 2, 1986, a site visit was conducted at the mining operations of the Cyprus Bagdad Copper Company located in Bagdad, Arizona. The objectives of the visit and tour were to gain familiarity with the Bagdad operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer
Robert Hearn - PEI Project Manager
Manford F. Swain - Cyprus Leaching Superintendent
James A. Sturgess - Cyprus Environmental Coordinator, Development

F.S. Mooney, Vice President and General Manager of Cyprus Bagdad Copper Company also participated in a portion of the meeting.

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Cyprus personnel provided a description of the facility's operations during the meeting and, afterward, conducted a tour of the operation. During the tour, additional, more detailed information about the leaching operation was provided. Photographs of the facility were taken by PEI and EPA during the tour.

General

The Bagdad mine is located approximately 110 miles northwest of Phoenix in western Yvapai County, Arizona. Initial open pit mining began at the site in 1956. The dump leaching operation began in 1960. Approximately 50,000 tons per day of ore is currently mined at the site, producing about 14 million pounds of copper annually. Between 8 and 10% of this copper is recovered from the dump leaching operation. The mine currently employs approximately 550 people.

Site Characteristics

The area surrounding the mine is relatively arid and consists of low rolling hills with minimal vegetation. The average seasonal temperatures range from 35° F in the winter to 95° F in the summer. The average annual precipitation is approximately 10 inches per year.

Western Yvapai County is relatively sparsely populated. The town of Bagdad is located adjacent to the mining operations and is comprised primarily of residences rented by the company to employees. Approximately 500 people currently live in Bagdad.

The ore body at Bagdad contains a chalcocite-enriched zone in a monzonite porphyry. Copper minerals mined at the site are largely chrysocolla, malachite and azurite with a little chalcocite enrichment.

Cyprus is currently operating 4 leach dumps. including the Alum Creek, Mineral Creek, Copper Creek and Niagara Creek dumps. These dumps contain approximately 600 million tons of ore and it is estimated that the leaching system has the capacity to hold an additional 300 million tons of ore.

Design and Management Practices

Low-grade, mine-run ore is used in the leach dumps. Ore having a copper content of at least 0.25% is generally deposited on the leach dumps. The dumps have been built directly upon the existing topography, utilizing the natural drainage created by the contours of several canyons located on the property to divert and collect the pregnant leach solution. There was no prior surface preparation of the dump sites.

Haulage trucks carry the ore from the pit to a leaching area where it is dumped and spread by a bulldozer. Lift heights range from 40 to 300 feet depending upon the particular topography of the land. After a lift is completed, the surface is ripped to a depth of about 5 feet and the solution distribution system is installed.

The leaching solution is distributed by a wiggler type sprinkling system. The solution consists of dilute H_2SO_4 (containing 8 gpl of H_2SO_4) having a pH of approximately 1.0. The flow rate from the sprinklers is about 3200 gpm. Initially, each lift is leached until the surface begin to pond due to a buildup of iron salt precipitates. After this period, the dumps are allowed to rest. The ratio between the leach period and the rest period is approximately 3:1. The pregnant solution is collected at the base of the each pile in an unlined reservoir. Pregnant solution from the Allum Creek reservoir is pumped to the top of the Copper Creek dump through which it is allowed to percolate. The pregnant solutions from the leach piles are then combined in an unlined pond. The pregnant solution from the pond is metered out through Niagara Dam into a trench and a collection reservoir The dam is made of concrete, and keyed into the bedrock of the surrounding hillside. Both the trench and the collection pond have been lined with 100 mil polyethylene liner. The pregnant solution collected in the reservoir is then pumped to the solvent extraction electrowinning (SX-EW) plant.

After the copper has been recovered in the SX-EW plant, the barren solution is recycled to the leach dumps. Approximately 100 tons per day of acid is added to this solution to reduce the pH. Mine water is used as makeup water.

Environmental Impact

The land upon which the dumps have been built was described as hard, impermeable rock. The overburden is post-mineralization alluvium, exhibiting relatively low permeability.

The depth of the groundwater was not known. However, between 500-800 gpm of water is produced in the mine pit. The mine water collected in the pit is used only in the mining operations as makeup water and is not discharged off the property.

The natural contours of the land divert the runoff from the surrounding hills around the mining and leaching operations. Precipitation falling within the mine area itself will be collected in either the pregnant solution collection ponds or the mine pit. An overflow floodplain reservoir has been constructed to protect against a hundred year flood event. Runoff collected in the floodplain reservoir is pumped into the pregnant solution collection reservoir and used in the leaching circuit.

There was no available groundwater monitoring information.

TRIP REPORT
NORANDA LAKESHORE MINES, INC.

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 3, 1986, a site visit was conducted at the mining operations of the Noranda Lakeshore Mines, Inc. The objectives of the visit and tour were to gain familiarity with the Lakeshore operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer
Robert Hearn - PEI Project Manager
John T. Kline - Chief Metallurgist, Noranda Lakeshore
Brent C. Bailey - Manager of Environmental Service, Noranda Lakeshore

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Lakeshore personnel also gave an overview of the operations after which a tour was conducted . During the tour, additional, more detailed information about the leaching operations was provided by Lakeshore personnel. Several documents dealing with the history and operations at the Lakeshore property were provided. In addition, a 308 study (308-FY86-009) recently conducted at the facility by EPA Region IX was cited. Portions of this report are taken from the information provided in those documents as well as subsequent conversations with Lakeshore personnel. Photographs of the facility were also taken by PEI and EPA during the tour.

General

The Noranda Lakeshore Mine is located in the Slate Mountains approximately 70 miles south of Phoenix and 60 miles northwest of Tucson.

The property consists of approximately 10,500 acres leased from the Papago Indian Tribe. The only activities currently being conducted at the site are an in situ mining operation and a solvent extraction-electrowinning (SX-EW) copper recovery plant. Approximately 3600 tons of copper are being produced annually by this operation.

Block caving operations began at the site in early 1970 and continued until 1977 when low copper prices resulted in a shut down. In 1979, Noranda Lakeshore Mines, Inc. acquired the property and full production was resumed. However, when low copper prices again caused a shutdown of the underground mining operations in 1983, the current in-situ operation was started.

Site Characteristics

The area surrounding the mine is typical Sonoran Desert climate and terrain. The average seasonal temperatures range from 53^{O}F and 87^{O}F. The average annual precipitation is 8 inches.

The property is located on a relatively sparsely populated indian reservation of the Tohono O'Odham Nation. The nearest community is North Komelik which is located 2.5 miles from the mine site and has a population of 125 people. The reservation upon which the mine is located contains about 973 people within a radius of approximately 12.5 miles.

The property contains three copper bearing bodies; three sulfide and one oxide. The initial block caving operations began in both the oxide and sulfide ore bodies. The ore deposit is covered with a thick, dense layer of fanglomerate consisting of silt, sand, and boulders and is bounded by two faults, the Lakeshore fault on the southeast and the 'C' fault on the west.

Design and Management Practices

The in situ leaching operation is being conducted in the existing block caved underground mine. The block caving operation has created a large subsidence area on the surface bounded on three sides by an 80^{O} enscarpment. The east side has been structurally controlled by the Lakeshore fault giving a scarp angle of 20^{O}. Test have indicated that the subsiding process has resulted in significant ore crushing, allowing better access to the leaching solution.

Considerable surface preparation was required to create an area accessible for drilling injection wells and the construction of well heads. Forty-four holes were drilled. All holes were sampled at five foot intervals. The casing installed in each of the holes is 1.5 inches diameter schedule 80 PVC pipe. Casing perforations start 20 feet below the fanglomerate.

Dams were placed across the No. 4, 5 and 6 haulage drifts at the 1100 level to contain the pregnant liquor solutions flowing from the extraction drifts. These dams were connected to the main dam at the shaft using 15 inch plastic irrigation pipe. Pregnant liquor solutions collected at the 900 level are pumped up to the 1100 level. The main pumping station is located at the 1100 level. Stainless steel pipes are used to pump the pregnant leach solution to the surface where the transition to polybutylene lines is made. The polybutylene pipes lay on the surface and run to the SX-EW plant.

Currently, the leach solution contains about 15 gpl acid and has a pH of about 1.3. Generally, the solution is pumped into the mine continuously. The pregnant leach solution recovered from the mine has a pH of about 1.95 and contains approximately 1.05 gpl copper.

Environmental Impact

The fanglomerate surrounding the ore deposit is a high acid consuming material and, therefore, any movement of the acid or heavy metals released by the acid should be restricted.

The depth of the groundwater ranges from 110 to 638 feet. Because of the depth of the block-caved area, the mine tends to act as a sump collecting water from the surrounding area. In addition, because of the size and extent of the subsidence, water runoff flowing into the area will tend to be collected in the haulage areas of the mined and collected with the pregnant liquor solution. There are no other runon/runoff controls.

TRIP REPORT
SILVER BELL MINE - ASARCO, INCORPORATED

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 3, 1986, a site visit was conducted at the mining operations of the Silver Bell unit of ASARCO, Incorporated. The objectives of the visit and tour were to gain familiarity with the Silver Bell operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer

Robert Hearn - PEI Project Manager

Scott L. Burrill - Director of Technology and Environment, ASARCO

Verle C. Martz - Environmental Engineer, ASARCO

David J. Duncan - Mill Superintendent, ASARCO

David F. Skidmore - Assistant to General Manager, ASARCO

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Silver Bell's personnel provided a description of the facility's operations after which a tour was conducted. During the tour, additional, more detailed information about the leaching operations was provided. Several documents outlining the operations at the facility were provided including a flow diagram, site plan and topographical map. Portions of this report are taken from the information provided in those documents as well as subsequent conversations with ASARCO personnel. Photographs of the facility were taken by PEI and EPA during the tour.

General

The Silver Bell mine is located approximately 40 miles northwest of Tucson in Pima County, Arizona. ASARCO began to acquire the properties in

1915 and underground operations were conducted at the site until 1921. The property was then idle until 1951, when preparations for the open pit operations began. Dump leaching began in 1960. Approximately 150 acres of the mine property are covered by leach dumps. Approximately 9,012,000 tons of copper are produced annually at the facility. Active mining of the site was suspended in August, 1984. The mine currently employs 48 people.

ASARCO is currently operating two leach dumps at Silver Bell. Approximately 21 million tons of low grade ore is currently being leached in the Oxide Leach Dump. This leach dump also includes an area containing 5.0 million tons of ore which will be leached in the future. The El Tiro Leach Dump currently contains approximately 40 million tons of ore.

Site Characteristics

Silver Bell lies to the west of the Avra Valley. The average seasonal temperatures range from 95^{O}F in the summer to 55^{O}F in the winter. The average annual precipitation is approximately 4 inches.

The property is located in a relatively sparsely populated area. Marana, with a population of approximately 1700, is located 25 miles east of the mine.

The rock surrounding the ore deposit at Silver Bell consists of monzonite, dacite porphyry and alaskite which have been hydrothermically altered, exhibiting the entire range of alteration features from propylitic through phyllic to potassic.

Copper mineralization in the enriched zone occurs primarily as chalcocite with lesser amounts of chalcopyrite along with minor covellite, cuprite, malacite, azurite and chrysocolla. Ore in the primary zone consists principally of chalcopyrite, with lesser amounts of bornite. Minor amounts of molybdenite, galena and sphalerite also occur in various parts of the ore zone.

Design and Management Practices

The ore deposited in the leach dumps contains between 0.3% and 0.4% total copper while the acid soluble copper is in the range of 0.15% to 0.30%. Since ore is not currently being mined from either of the pits, operation of the dump leach circuit and the recovery of copper in cementation cells are the only activities being conducted at the facility. Periodically, the surface of each of the dump areas is ripped to a depth of approximately 6 feet and the ore is mounded to form troughs and ponds into which the leaching solution can be pumped. The leach solution is then applied to the dump utilizing the ponding method for a period of 6 to 12 months until the precipitation of iron salts prevent the infiltration of leaching solution into the pile. At the end of that period, the dump is allowed to "rest" for a period of 5 to 12 months after which the cycle is begun again. Only about 40% of the leach dumps are being leached at any one time.

The dumps are leached with a solution of dilute H_2SO_4. The solution contains about 0.15 gpl of acid and has a pH of approximately 2.8. Between 0.75 and 0.80 lb. sulfuric acid is used for each pound of recovered copper. Operational and seasonal variations result in solution flow rates ranging from 2000 gpm to 2500 gpm.

The pregnant liquor is collected at the toe of the dumps in unlined holding ponds situated on bedrock. An example of the characteristics of the pregnant leach solution are as follows:

Copper	0.80 gpl
H_2SO_4	0.50 gpl
Ferrous iron	0.01 gpl
Ferric iron	0.60 gpl

The pregnant solution is pumped from the holding ponds to a collection reservoir . The leach dumps produce approximate 2200 gpm of pregnant liquor. The combined solutions are then pumped through epoxy lined pipes to the cementation operation.

The pH of the barren solution from the cementation operation is approximately 3.5. Makeup acid is added to the barren solution before it is pumped into an unlined holding pond. Although the barren solution from the cementation cells is clear, the iron salts that have precipitated from solution and line the sides and bottom of the pond gives the resulting brown appearance. The solution is pumped, as needed, from this holding pond to the leach dumps as feed solution.

Environmental Impact

The leach dumps are sited on the rocky hillsides. There was no special surface preparation prior to building the dumps . All retaining dams are constructed of concrete and have been keyed into the bedrock to prevent seepage.

There is no aquifer underlying the site.

Runoff and seepage is contained in overflow and catchment dams which have been constructed downgradient of the leach solution and barren solution holding ponds and leach dumps. Solution volume in the circuit is controlled to address varying weather conditions, so as to absorb rain that may fall within the localized water shed.

TRIP REPORT
INSPIRATION CONSOLIDATED COPPER COMPANY

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 4, 1986, a site visit was conducted at the mining operations of the Inspiration Consolidated Copper Company. The objectives of the visit and tour were to gain familiarity with the Inspiration operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in both the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer
Robert Hearn - PEI Project Manager
Jack Castner - Senior Environmental Engineer, Inspiration
Tom B. Larsen - Manager of Environmental Affairs, Inspiration

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Inspiration personnel provided a description of the facility's operations during the meeting after which a tour of the operation was conducted. During the tour, additional, more detailed information about the leaching operation was provided. Inspiration also provided PEI with several articles describing the operations at the facility. In addition, photographs of the facility were taken by PEI and EPA during the tour. This trip report will include information contained in those articles as well as information obtained in subsequent conversations with Inspiration personnel.

General

The Inspiration mine is located between the towns of Claypool and Miami, about 75 miles east of Phoenix, in Gila County, Arizona. The mine was originally a block cave operation, but is presently active only as an open pit mine. Dump leaching was introduced at the Inspiration mine in 1955.

Inspiration's mining operations include the Barney, Thornton, Joe Bush, Live Oak, Upper and Lower Ox Hide, and the old Bluebird pits. Of these, only the Bluebird pit is active. The Bluebird pit was acquired from Ranchers Exploration and Development Corporation in July, 1984. Approximately 80,000 tpd of ore is being mined at the Bluebird pit. The Live Oak pit is being dewatered.

Site Characteristics

The mine is located in the Mescal Mountains at an altitude of approximately 4000 feet. The average seasonal temperatures range from 95^{O}F in the summer to 50^{O}F in the winter. The average annual rainfall is approximately 20 inches per year.

The towns of Claypool and Miami, with a total population of approximately 5500, are located across U.S. Highway 60-70. Water for these residences is supplied from wells operated by the Arizona Water Company located approximately 3-5 miles from the site.

The host rock for the ore is granite schist. The principal copper minerals mined at the site are malachite, azurite and chrysocolla with minor amounts of chalcocite and chalcopyrite.

Design and Management Practices

Inspiration operates two separate leach circuits: a conventional dump leaching operation and a ferric cure leaching operation. Ore containing above 0.3% copper as chalcocite and oxides is delivered to the ferric cure circuit while ore containing less than the 0.3% copper cutoff is delivered to the conventional leaching circuit. These circuits are operated in series, i.e. the pregnant leach solution recovered from the conventional operation is used as the leaching solution for the ferric cure operation.

The leach dumps in the old Inspiration property were deposited on the existing topography. The underlying surface was cleared of existing vegetation and graded to channel the pregnant leach liquor into the collection ponds located at the toe of the pile. The underlying surface of the old Bluebird leach dumps was also cleared of vegetation and dressed after which the soil was cemented and covered with dilute tar for curing and sealing.

New lifts of leach material are built on previously leached dump piles. Prior to the placement of a new lift, the surface of the dump is ripped to a depth of approximately six feet. The ore is then hauled to the pad by trucks and spread with bulldozers. After the lift has been completed, the surface of the lift is ripped and the solution distribution piping is laid.

The distribution system consists of 2 inch piping perforated with 1/8 inch holes to allow for distribution of the leaching solution. The leaching solution contains approximately 5-15 gpl H2SO4 and has a pH of 1.0. It is applied to each lift for a period of up to 125 days at varying flow rates. A flow rate of approximately 15,000 gpm is maintained for the entire system.

The leaching techniques used in the ferric cure operations are unique in that the leach pads are carefully constructed in uniform dimensions. The leach pads are generally rectangular, measuring approximately 250 feet wide x 600 feet long. A pad is stacked to a height of approximately 30 feet. After completion of the pad, the pile is cured. The cure solution contains 200 gm/liter H2SO4 and 2-3 gm/liter ferric iron. Sufficient cure solution is applied to saturate the pad in two separate applications. The pad is then allowed to "cure" or rest for 15 days, after which it is rinsed with conventional leach solution for up to 120 days. It is estimated that at the end of the leaching cycle, approximately 70% of the copper has been recovered.

The leach solutions from each of the leaching circuits are collected in ponds at the base of each dump. All of the retaining dams used to hold the pregnant solution are made of concrete with either clay or concrete cores. All of the dams have been keyed into the bedrock in the existing hillsides to prevent leakage.

The pregnant solution collected in the ponds is pumped to a solvent extraction/electrowinning plant for copper recovery. The SX-EW plant currently receives and processes approximately 4500 gpm of pregnant liquor. The barren solution or raffinate produced by the SX-EW plant is then recycled into the conventional leaching circuit.

Environmental Impact

The majority of the leach dumps have been built upon the existing topography. In addition, most of the collection reservoirs are unlined. The surface upon which the dumps and collection ponds have been constructed was described, however, as a tight formation of bedrock and, therefore, relatively impermeable.

Diversion ditches have been dug around some of the dumps to divert runoff from the piles into collection ponds. In addition, diversion ditches have also been dug to divert surface runoff from outside the property away from the dumps.

TRIP REPORT
PINTO VALLEY COPPER CORPORATION

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 4, 1986, a site visit was conducted at the mining operations of the Pinto Valley Copper Corporation, a subsidiary of the Newmont Mining Corporation. The objectives of the visit and tour were to gain familiarity with the Pinto Valley operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer
Robert Hearn - PEI Project Manager
Robert G. Ingersoll - Environmental Engineer, Pinto Valley
Norm Greenwald - Chief Environmental Engineer, Newmont
Gene Santellanes - Leaching General Foreman, Pinto Valley
Chris Erskine - Senior Hydrologist, Pinto Valley

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. During the meeting, Pinto Valley personnel gave an overview discussion of the operations. A tour of the operation was then conducted. During the tour, additional, more detailed information about the leaching operation was provided. Pinto Valley provided PEI with an article describing the operations at the facility. In addition, photographs of the facility were taken by PEI and EPA during the tour. This trip report will include information contained in that article as well as information from subsequent conversations with Pinto Valley personnel.

General

The mining operations of the Pinto Valley Copper Corporation are located about 70 miles east of Phoenix in Gila County, Arizona. The property includes the Castle Dome, Miami, and Copper Cities mines which were acquired from Cities Services Company in 1983.

Initial open pit mining began at the Pinto Valley site around 1972. Active dump leaching operation began in 1981 when construction of the solvent extraction plan was completed. The operation currently covers an area of approximately 6570 acres of which 470 acres are cover by leach dumps. Approximately 85,000 tons of copper are produced annually from the Pinto Valley operation, 15% of which is produced from the leaching operation.

Leaching at the Pinto Valley site consists of seven waste dumps. The dumps currently contain approximately 297 million tons of leachable waste ore. About 28 million tons of leachable waste are being added to the dumps each year.

Conventional mining at the Miami mine ended in 1959. In situ leaching began on a small scale in 1942 with full-scale leaching beginning when the underground mine was closed in 1959.

The Copper Cities unit consisted of an open pit operation and concentrator that were active between 1954 and 1975. All mining and milling operations ceased in late 1975. Dump leaching began in 1962 and continued until June, 1982.

Site Characteristics

The mines are located at an altitude of approximately 4000 feet above sea level. The average seasonal temperatures range from 95 degrees in the summer to 50 degrees in the winter. The average annual precipitation is approximately 20 inches per year.

The towns of Claypool and Miami, with a total population of approximately 5500, are located adjacent to the Miami property across U.S. Highway 60-70 and within ten miles of the Pinto Valley and Copper Cities sites. Water for these residences is supplied from wells operated by the

Arizona Water Company located approximately 3-4 miles from the Miami unit and 10-12 miles from the Pinto Valley operation. There is no identifiable aquifer under the property.

The host rock for the ore at the Pinto Valley site is quartz monzonite and granite porphyry. The principal copper minerals mined at the site are chalcopyrite and chalcocite with minor amounts of covellite, cuprite, azurite, and malachite.

The host rock for the deposit at the Miami mine is Precambrian Pinal Schist, which is partially covered by the Gila Conglomerate. The area is highly faulted and fractured. The principal copper mineral is chalcocite with minor amounts of chalcopyrite,bornite, covellite, mamachite, azurite, chrysocolla, cuprite and native copper.

The host rock for the Copper Cities mine ore deposit is quartz monzonite. The principal copper minerals are chalcocite and chalcopyrite with minor amounts of covellite, turquoise, malachite and azurite.

Design and Management Practices

The leach dumps at the Pinto Valley site have been constructed on existing topography with no prior subsurface preparation. Currently, only about 70 acres of the dumps are being leached at the Pinto Valley site. Trucks haul the material from the mine pit to the leach dump. After each lift is completed, the surface is ripped to a depth of approximately 3 to 4 feet using a cat ripper and the distribution system is installed. The distribution system consists of 2 inch perforated Drisco pipe spread over the dump.

The leach solution applied to the Pinto Valley dumps contains approximately 2.25 gpl H_2SO_4 and has a pH of around 1.7 to 1.8. It is applied continuously until the surface of the dump begins to pond, indicating excess precipitation of iron salts. The pregnant leach liquor contains about 0.95 gpl H_2SO_4 and has a pH of about 2.0 to 2.1 and is collected in the drainage below the dumps. Pumps lift the solution through one mile of pipe to the solvent extraction-electrowinning (SX-EW) plant.

The ore body at the Miami site is leached in place, using the old underground mining works. The leach solution is percolated through the caved area by underground injection and surface spraying. The pregnant leach liquor is collected at the 1000 ft. haulage level. and pumped to the surface. The operation produces approximately 2900 gpm of pregnant leach solution.

The pregnant leach solution contains 0.57 gpl of H_2SO_4 and has a pH of 2.2. The raffinate from the solvent extraction plant contains 1.6 gpl H_2SO_4 and has a pH of 1.7 to 1.8. The raffinate is recycled back to the caved area for distribution as part of the leach solution.

Environmental Impact

The leach dumps have been built on the existing topography and the collection reservoirs are unlined. The subsurface area upon which the leaching operation is conducted consists of bedrock according to company personnel.

Pregnant liquor from the leach dumps at the Pinto Valley site is collected in an unlined reservoir behind Gold Gultch Dam #1. An overflow catchment dam, Gold Gultch Dam #2, has been constructed down the valley to retain any flows that may result from an upset condition. Both dams have a rock shell with a clay core and are key cut grouted to bedrock.

The Miami mine's in situ operation has a positive water balance indicating that the underground mine is acting as a sump, collecting water from surrounding areas and, at least in part, preventing the migrating of leachate away from the mined area.

Diversion ditches and collection ponds have been constructed around the entire Copper Cities leach pile to catch any run-off and leachates. Overflow catchment dams have been constructed to retain any flow from these containment areas during any upset conditions. Solutions collected in the ponds and catchment areas are diverted to the inactive tailings ponds where the liquid is evaporated.

TRIP REPORT
RAY MINES DIVISION
KENNECOTT COPPER CORPORATION

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 5, 1986, a site visit was conducted at the mining operations of the Ray Mines Division of Kennecott Copper Corporation. The objectives of the visit and tour were to gain familiarity with the Kennecott operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer
Robert Hearn - PEI Project Manager
C.S. Fitch - Director of Safety & Environmental Control,
Ray Mines Division
Gerald Schurtz - Kennecott Copper Corporation
Neil Gamble - Acting Mining Manager, Ray Mines Division
Bobby Armenta- Safety and Environmental Control Supervisor,
Ray Mines Division

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Kennecott personnel provided a description of the facility's operations during the meeting and then conducted a tour of the operations. During the tour, additional, more detailed information about the leaching operations was provided. Kennecott provided PEI with several documents describing the operations at the facility. In addition, photographs of the facility were taken by PEI and EPA during the tour. This trip report will include information contained in that article as well as information from subsequent conversations with Kennecott personnel.

General

The mining operation of Ray Mines Division is located in east central Arizona approximately 75 miles southeast of Phoenix. and 70 miles north of Tucson in the Mineral Creek Mining district of Pinal County. It lies in the Mineral Creek valley approximately five miles north of the Gila River.

Underground mining activity at the site began around 1880 and continued sporadically until 1948 when it was decided that the Ray ore body could better be mined by open pit methods. The transition from underground to open pit mining was completed in 1955. Mining activity is currently being conducted in the West Pit and the Pearl Handle Pit. There are currently five active low grade copper sulfide ore leach process areas and one active copper silicate ore leaching area.

Site Characteristics

The Ray Mine and associated ore leaching operations are constructed on the west side of Mineral Creek Valley, in a surface water flow channel restricted by bedrock. The average seasonal temperatures range from 85-95°F in the summer to 50-60°F in the winter. Average annual precipitation in the area is about 17.5 inches.

The Ray mine is underlain by bedrock, primarily by the Precambrian Pinal Schist. The Pits and surrounding bedrock are relatively dry from a hydrogeologic perspective. No alluvial aquifers exist. Water is present at depth in isolated fracture zones, but none of the bedrock formations are capable of supplying significant or sustained yield.

The Gila River receives all drainage in the area and flows southwest to the Ashurst-Hayden diversion dam near Florence, approximately 15 miles below Kelvin, where the river is totally diverted for use as agricultrual irrigation water. Mineral Creek, which was the original drainage course through the Ray Mine, meets the Gila River at the town of Kelvin. In order to prevent contamination of Mineral Creek and the Gila River, Kennecott has constructed a large flood control and diversion dam north of the mine site which diverts the flow of the Mineral Creek into a 3.4 mile concrete tunnel which conveys the flow of the Mineral Creek around the mine site and discharges the flow back into the creek below the mine.

Chalcocite has been the main copper mineral in ore from the Ray deposit. Minor amounts to covellite are also present. Chrysocolla and other copper silicates are also relatively abundant. Pyrite is ubiquitous throughout the ore.

Design and Management Practices

Approximately 1100 acres are available for the low grade copper sulfide ore leaching processes; only 10-15 percent of which is being flushed with water at any one time. The remaining area is at rest under oxidizing conditions. The dump leach piles are located directly on the existing topography. There was no special surface preparation prior to the deposition of dump material.

Mine-run ore is hauled to the leach piles by truck and spread with bulldozers. After each lift is completed, the surface of the pile is ripped to depth of approximately 5 feet and, depending upon the solution distribution method, trenched. The leach solution is distributed by either sprinkling or border irrigation. The choice of distribution method depends upon the pump capacity available for the particular leach area.

The leach solution is applied to a pile until it begins to pond due to the precipitation of iron salts on the surface. This usually takes approximately 10 weeks.

The solution applied to the dumps has a pH of 3.5. It is delivered to the dumps at 8700 gpm and applied through a series of flapper sprinklers. The pregnant liquor is collected in unlined ponds from which it is pumped to either the North or South precipitation plants. The pregnant liquor generally contains approximately .42 gpl acid and has a pH of 2.8. The tail water from the precipitation plants is redistributed onto the leach surfaces.

The copper silicate ore leaching operation is used to recover copper from copper silicate mineralized ores. Prior to building the 70-foot heap, the previous heap is ripped. Mine-run ore is delivered by haulage trucks to the primary crusher which reduces the ore to minus 8-inch size. The crushed ore is then conveyed to an open air coarse ore stockpile. The crushed ore is then conveyed to a secondary/tertiary crushing facility which reduces the ore to minus 7/16 inch. This fine crushed product is then conveyed to a fine ore building, which has a capacity of approximately 35,000 tons.

The crushed ore is fed from fine ore storage onto a series of conveyors which move the ore to an area adjacent to the copper leaching area. The ore is also prewet with a solution of water and 18-19 gpl H_2SO_4. Trucks then load and transport the ore to the heap site. Each heap contains approximately 40,000 tons of crushed ore.

The leaching solution, containing 18 gpl H_2SO_4, is delivered to the heap leach site at 3000 gpm and applied to the ore heaps through a series of sprinklers. Each lift is leached for 42 days. The pregnant liquors, which contain approximately 4.5 gpl acid and 3.6 copper, are collected in unlined ponds and pumped to the solvent extraction-electrowinning (SX-EW) plant.

Environmental Impact

The entire Ray Mine area is underlain with bedrock. All solution recovery dams are keyed into bedrock to ensure containment of pregnant solutions. Dams and associated pipelines which lie above gradient are designed to flow into pit containment areas during any upset condition. Dams lying down gradient of the headwater reservoirs are equipped with primary and backup pumping capability. In the event this capability is lost or is insufficient for incoming flows, each dam is designed to overflow into the plastic lined Big Dome reservoir, an 18 million gallon capacity pond.

The pregnant leaching solutions from the leach dumps is retained by a dam constructed across the down-gradient side of the drainage channel. Waters which might overflow the leach dams are collected in Big Dome reservoir. Process water spills and runoff from process areas would also be contained in this pond. This water is either pumped back to the leach dumps or treated at the lime neutralization/precipitation facility.

All natural surface and groundwater drainage from the area would be via Mineral Creek and its subflow and would be confined by the narrow bedrock boundaries of Mineral Creek. Diversion ditches have been constructed around the sulfide ore leach dumps located west of the open pit workings to minimize the amount of surface water entering the process water system.

An estimated 1 billion gallons of water are in storage in the mine pits. Both pits are confined by bedrock and are located well below the elevation of Mineral Creek.

Mine overburden is separated into barren and copper-bearing portions. Only barren material is placed on those dumpsites on the northeast side of the mine to prevent pollution of Mineral Creek from dump drainage.

TRIP REPORT
SAN MANUEL MINE - MAGMA COPPER COMPANY
EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On June 5, 1986, a site visit was conducted at the mining operations of the San Manuel Mine owned by the Magma Copper Company. The objectives of the visit and tour were to gain familiarity with the San Manuel operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Jack Hubbard - U.S. EPA Project Officer
Robert Hearn - PEI Project Manager
Dave Baker - Environmental Engineer, Newmont
Marcel F. DeGuire - Director of Environmental Affairs, Newmont
Harry Smith - Mine Supervisor, Newmont
Charles O'Coyne - Assistant Superintendent
Chris Burt - Project Engineer (In situ operation), Magma

Newmont personnel provided a tour of the facilities during which information about the leaching operation was provided. Photographs of the facility were taken by PEI and EPA during the tour. This trip report includes information provided during the tour as well as information from subsequent conversations with Newmont personnel.

General

The San Manuel mining operation is located in southeast Arizona approximately 40 miles north of Tucson. Undergrornd mining of the site began in June, 1956. An open pit operation was begun in 1985. Leaching operations began in April, 1986.

Site Characteristics

The area surrounding the mine is relatively arid with low rolling hills dissected by erosions gullies and covered with minimal vegetation. The average seasonal temperatures range from 95^{0} F in the winter to 50^{0} F in the summer. The average annual precipitation is 10 inches per year. The Water Table for the area is between 1200 and 2500 feet below the surface.

Approximately 99% of the ore mineralization in the open pit operation is chrysocolla. All of this ore will be leaching at a site which will eventually contain a total of 55 million tons of low-grade ore.

Design and Management Practices

The area selected for the leach dump area is within the cone of depression created by the underground mining activity. The area was first stripped of all vegetation and graded to eliminate steep hills and drain into ditches which would divert the solution collection pond. The surface of the area consisted of Gila Conglomerate which was used as the subgrade for a synthetic liner. This material was compacted using rollers and compactors to crate a smooth even surface. Internal dams where also built onto the terrain using the Gila Conglomerate which, after placement of the liner, would isolate any failures in the liner and prevent excess solution loss. French drains were also keyed into the natural terrain to channel solution out of the dump area to a collection pond or into the subsidence area of the underground mine.

The liner is made of 60 or 100 mil of of high density polyethylene. This was selected because of its tensile strength and flexibility. The 60 mil material was used over ridges of the dump while the 100 mill liner was used in the solution collection areas. After the liner has been installed, the seams were sealed using a heat gun and "extrusion machine.' This seam was then vacuum tested and splices were taken every hundred feet for additional testing in a laboratory. A walking inspection was also made of the liner to identify any punctures or large rocks under the liner which might cause it to tear. Any problems areas located were fixed.

After the liner was completed, a collection system of pipes was layed in the collection trenches. This system consisted of 4 inch performated HDPE pipes connected to main collection pipes of 18 to 24 inch HDPE. A mixture of sand and graded stone was then placed over the pad to a depth of 18 inches to protect it from damage by earth moving equipment, to provide a permeable drainage blanket and to reduce excessive pressure points on the liner. The size of the gravel was between approximately +1 inch and - 3 inches.

Mine-run ore from the open pit operation is hauled and dumped on the pad by trucks and spread with a bulldozer. The ore is piled in 20 foot lifts . Each lift is substantially rectangular in shape. After a lift is completed, it is ripped to a depth of approximately 9 feet and the solution distribution system is then installed.

The leaching solution is distributed through 3 inch pipes connected to wobbler sprinklers. The solution consists of dilute H2SO4 (containing 10 gpl of H2SO4) having a pH of not greater than 2.0. The flow rate from the sprinklers is adjusted to be approximately 1.5 gallons of leaching solution for each 100 sq. ft. Initially, each lift will be leached for a period of 60 days. After this period, each lift will be allow to sit for a period before the surface is ripped and another lift is added. The maximum height of each dump pile is anticipated to be approximately 280 feet.

The pregnant solution is expected to contain approximately 1.6 gpl free acid and 1.3 gpl copper. It will be collected in the perforated pipes under each of the dumps which will direct the flow into a lined reservoir. The pregnant solution collected in the reservoir is then pumped to the solvent extraction-electrowinning (SX-EW) plant.

After the copper has been recovered in the SX-EW plant, the copper content of the barren solution or raffinate is about 0.10 gpl or less. The raffinate also contains about 7 gpl acid. After adding acid, the solution is recycled to the leach dumps.

Environmental Impact

As long as the integrity of the liner remains intact, the escape of the pregnant liquors and runoff from the piles into the groundwater should be minimal. If there should be a power failure or a major upset event, the collection reservoir will overflow into the subsidence area created by the underground mining operation. Since the lowest level of the underground mining activity is at least 100 feet below the water table, the mine acts as a sump drawing water from the surrounding area and therefore preventing the spread of any subsurface contamination.

TRIP REPORT
TYRONE MINE
PHELPS DODGE CORPORATION

EPA Contract No. 68-02-3995
PN 3650-25

Prepared by
PEI Associates, Inc.

On August 13, 1986, a site visit was conducted at the mining operations of the Tyrone Branch of Phelps Dodge Corporation located near Silver City, New Mexico. The objectives of the visit and tour were to gain familiarity with the Tyrone operation and to discuss the current copper leaching project being conducted by PEI for the U.S. Environmental Protection Agency. The following personnel participated in the meeting and tour:

- Robert Hearn - PEI Project Manager
- Judy McArdle - PEI Environmental Engineer
- Michael Koranda
- David Kimbal
- David Horton

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Tyrone personnel provided a description of the facility's operations during the meeting and conducted a tour of the operation. During the tour, additional information about the leaching operation was provided. Several documents dealing with the leaching operation were also provided. Portions of the report are taken from the information provided in those documents as well as subsequent conversations with Tyrone personnel. Photographs of the facility were taken by PEI during the tour.

General

The Tyrone mine is located approximately 10 miles south of Silver City in Grant County, New Mexico. The operation includes three open pits covering approximately 730 acres, a mill, leach dumps, precipitation plant and solvent extraction/electrowinning plant. Operations at the site began in 1969. Leaching of the first dump began in 1971.

Site Characteristics

The mine is located in the southern Rocky Mountains. The area is characterized by low mountain ranges with adjacent, flat-floored valleys. The area is semi-arid with penion, oak and juniper vegetation. The elevations at the site range from 6450 feet at the dump sites to 5150 feet in the Mangas Valley at No. 3 tailing pond. The average annual rainfall is approximately 20 inches and seasonal temperatures range from 67^{o}F to 41^{o}F.

Chalcocite is the most important mineral in the ore body. Significant amounts of pyrite, chacopyrite and sphalerite also occur in the sulfide zone of the ore body. Chrysocolla is the most abundant mineral in the oxidized zone.

There is an aquifer in the bedrock in the area of the leach dumps. This aquifer is of generally low yield with porosity the result of fracturing and faulting. The Burro Chief Fault in the mine area acts as a barrier to ground flow to the west. The depth of the groundwater generally ranges between 50 and 500 feet.

Design and Management Practices

The leach dumps are generally located along the perimeter of the mine. Three dumps are currently in operation (1, 1-A, 2), two are under construction (1-B, 3) and two dumps are proposed (2-A, 1-C). The size of these dumps are set forth below:

1	140 acres
1-A	120 acres
1-B	212 acres
1-C	285 acres
2	807 acres
2-A	509 acres
3	267 acres

Most of the existing dumps are located on the existing topography. Dumps 1 and 3, however, have a partial clay pad to prevent seepage and minimize potential groundwater contamination. Generally, the clay liner under these dumps are placed only in areas having slopes less than 5:1. The pregnant liquor (PLS) ponds for Dumps 1, 1A, 1B and 2 are also lined with clay. The proposed PLS pond for Dump 3 will be lined as well.

As previously noted, No. 3 dump is 267 acres. Approximately 29 acres are located directly on bedrock having a conductivity of 1.8×10^{7} ft/sec. 109 acres were scarified and recompacted to a conductivity of 3.8×10^{8} ft/sec., and 37 acres were lined with clay and aluminum from the valley floor to achieve a conductivity of 2.2×10^{9} ft/sec. Approximately 92 acres remained untreated. The clay liner consisted of 18 inches of compacted soil placed in 6 inch lifts. The minimum lines content of the soil was 12% and the moisture content was $\pm 2\%$ of optimum. The soil was compacted to 98% of its maximum dry density. Lose on-site soil was placed on top of the liner to a depth of 1.5 feet to protect it and keep it from drying out.

Generally, the ore is hauled to the dumps by truck. Approximately 42,000 tons of leach material is hauled to the dumps each day. This material has an average copper content of 0.31%. After the ore has been dumped, it is spread by bulldozer and, after completion of each lift, is ripped to a depth of approximately 5 feet to improve the permeability of the surface.

The leaching solution is applied to the piles by both spraying and ponding. The application rate for spraying is 300 gpm/acre while the rate for ponding is 900 gpm/acre. The leaching reagent is water derived from the raffinate generated by the solvent extraction process plus make-up water, if necessary, from wells. The pH of the leaching reagent averages approximately 2.4 and contains 4-5 gpl of sulfuric acid.

The pregnant liquor solutions from Dumps 2, 2A and 3 are collected in ponds and pumped to a solvent extraction/electrowinning (SX-EW) plant. The SX-EW plant is currently handling approximately 6600 gpm of solution.

Environmental Impact

Each of the dumps, except Dump 1, are permit under the New Mexico Water Quality Control Regulations. Consequently, each of the operating dumps is currently monitored by wells as follows:

Dump	Monitoring Wells
1A	3 wells (normally dry)
1B	7 wells (1 deep well 2 aquifer monitor wells 4 neutron access tubes)
2	12 wells
3	10 wells

Effluent quality is sampled by these wells and report and reported as part of each dumps discharge plan requirement.

Each of the PLS ponds have overflow ponds (unlined) to collect any overflow from the ponds to a rainfall event or equipment malfunction.

Portions of Dumps 1, 2 and 3 are lined with clay and most of the PLS ponds are also lined.

TRIP REPORT
CYPRUS JOHNSON COPPER COMPANY

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On August 13, 1986, a site visit was conducted at the mining operations of the Cyprus Johnson Copper Company near Benson, Arizona. The objectives of the visit and tour were to gain familiarity with the Cyprus Johnson operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Robert Hearn - PEI Project Manager
Judy McArdle - PEI Environmental Engineer
Rana Medhi - Cyprus Johnson Resident Manager
Bill Rudy - Cyprus Johnson SX/EW Plant Superintendent
Tony Gomez - Cyprus Minerals Co. Environmental Coordinator

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Cyprus Johnson personnel provided a verbal description of and written handouts pertaining to the facility's operations after which a tour was conducted. During the tour, additional, more detailed information about the leaching operations was provided. Photographs of the facility were taken by PEI during the tour.

General

Cyprus Johnson's open pit mine and heap leaching operation are located approximately 15 miles northeast of Benson, Arizona, in Cochise County. Mining of the predominantly oxide ore began in 1975 and was discontinued in January 1984. Although no new ore is being added to the piles, copper continues to be recovered from the existing material by sulfuric acid leaching and solvent extraction/electrowinning. Annual capacity of the SX/EW plant is rated at 10 million pounds of cathode copper. The plant, which employs 17 people, is currently operating at 50 percent capacity and is scheduled to shut down permanently in December 1986. No facilities for processing sulfide ore by conventional milling, concentrating, and smelting have ever existed at this location.

Copper is leached from two ore heaps located immediately southwest of the mine. The No. 1 pile was started in 1975, and the No. 2 pile was started in 1980. Combined, these heaps contain an estimated 15.2 million tons of leach material and have a total surface area of approximately 42 acres. The mine waste dump is located just northeast of the pit and occupies an area of 80 acres.

Site Characteristics

The Cyprus Johnson mine site is located at the base of the Little Dragoon Mountains (elevation 5030 feet). The average seasonal temperatures range from 48°F in the winter to 80°F in the summer. The average annual precipitation is approximately 12 inches.

The area in the vicinity of the mine is sparsely populated. The town of Benson (pop. 4200) is located approximately 15 miles southwest of the site, and the town of Willcox (pop. 3200) is located some 15 miles in the opposite direction.

The copper mineralization occurs primarily as fracture filling in tilted paleozoic sediments (Lower Abrigo shale). The most abundant mineral is chrysocolla with lesser amounts of other secondary oxides of copper, including tenorite, malachite, azurite, cuprite, and rarer amounts of dioptase. There is no aquifer present beneath the leach areas.

Design and Management Practices

During the active life of the mine, ore containing greater than 0.4 percent total copper was hauled by truck from the pit to the No. 1 and No. 2 leach piles and spread by bulldozer. The two leach heaps, which are located in natural drainages, were built in successive lifts of 4 to 5 feet. The Number 1 heap ranges in height from 145 to 250 feet; the Number 2 heap averages 63 feet in height.

Leaching of the two ore heaps proceeds in stages (see Figure 1). Approximately 2100 gpm of a dilute sulfuric acid solution (0.5 to 1.5 percent H_2SO_4) is pumped to the top and sides of the No. 1 heap and distributed by means of 3/4-inch-diameter HDPE drip tubing. The pregnant liquor (0.5 gpl Cu; pH 2.3) is collected at the toe of the pile in the 4,400,000-gallon PLS pond. The pond is constructed over quartzite bedrock, and the face of the earther dam is lined with 30-mil hypalon. From the PLS pond, the copper-bearing solution is delivered to the top and sides of the No. 2 heap. The pregnant liquor (0.75 gpl Cu; pH 2.5) is collected in the 8,000,000-gallon middle pond, which is located between the two leach heaps. The middle pond is also constructed over quartzite bedrock. The pregnant liquor from the middle pond is fed to the SX plant, where approximately 93 percent of the copper is extracted from solution. The barren solution is then directed to the 2,500,000-gallon raffinate pond, where makeup water and acid are added at a rate of 125 gpm and 6 gpm, respectively. The raffinate pond is constructed on quartzite bedrock and lined with a 4-inch-thick layer of acid-resistant gunite. The raffinate is recirculated from the pond to the No. 1 heap, and the leach cycle is repeated.

Environmental Impact

The No. 1 and No. 2 leach heaps were constructed in natural drainages over "tight" quartizite bedrock. The PLS pond, middle pond, and raffinate pond were also constructed over bedrock. The raffinate pond is lined with 4 inches of gunite; the other two ponds are not lined. There is no ground-water aquifer beneath the leaching or mining operations.

Storm water runoff is collected in two catchment ponds (earthen dams with total capacity of 9,640,000 gallons), located upstream of the heap leach area, as well as in the PLS, middle, and raffinate ponds. Overflow from the catchment ponds, the raffinate pond, and the middle pond is diverted around the ore heaps to the next downstream pond. Overflow from the PLS pond runs into the overflow catchment pond (earthen dam constructed over bedrock with a capacity of 2,800,000 gallons). The system of storm water runoff ponds has been designed to completely contain the 10-year, 24-hour storm. Facility personnel state that the overflow catchment pond has been filled to 50 percent only twice since 1975.

TRIP REPORT
BINGHAM CANYON MINE - KENNECOTT COPPER CORP.

EPA Contract No. 68-02-3995
PN-3650-25

Prepared by
PEI Associates, Inc.

On August 15, 1986, a site visit was conducted at Kennecott Copper Corp.'s Bingham Canyon Mine in Bingham Canyon, Utah. The objectives of the visit and tour were to gain familiarity with the Bingham Canyon operation and to discuss the current copper leaching project being conducted by PEI for the EPA. The following personnel participated in the meeting and tour:

Robert Hearn - PEI Project Manager
Judy McArdle - PEI Environmental Engineer
Gerrald Schurtz - Kennecott Manager of Environmental Health
Steven Taylor - Kennecott Manager of Environmental Engineering
Gary Jungenberg - Kennecott Precipitation Plant Superintendent

An initial meeting was held to discuss the EPA's mine waste program in general and the current project in detail. Kennecott personnel provided an overview of the facility's operations and a helicopter tour of the area. During the tour, additional, more detailed information about the leaching operations was provided. Aerial photographs of the facility were taken by PEI during the tour.

General

Kennecott's Bingham Canyon mine is located in Bingham Canyon, Utah, approximately 20 miles southwest of Salt Lake City. Open-pit mining of the copper porphyry ore body began in 1904 and has continued for more than 80 years. (Mining was temporarily suspended in March 1985 for economic reasons and resumed in October 1986. The Bingham Canyon mine has the distinction of being the largest open-pit mine in the world--it covers an area of about 1400 acres (2.2 square miles) and is more than 0.5 mile deep. When active, approximately 106,000 tons of ore, 360,000 tons of leach material, and 20,000 tons of waste rock are removed from the pit each day.

Dump leaching and cementation operations at the Bingham Canyon mine were initiated in 1923. The leach dumps (east and west) currently occupy approximately 2110 acres (3.3 square miles) and contain an estimated 1500 million tons of material. Annual precipitate production in 1985 was 17,000 tons. Currently, only the east dumps are being leached. Leaching of the west dumps was suspended indefinitely in 1984. The carbonaceous material in the south dumps is not leached.

In addition to the mine, leach dumps, and precipitation plant, Kennecott operates a crushing plant, two concentrators, a smelter, an electrolytic refinery, and a tailings pond. These operations are located 15 miles north of the mine site.

Site Characteristics

The Bingham Canyon mine is located in the Oquirrh Mountains in north central Utah. The average seasonal temperatures range from 31°F in the winter to 70°F in the summer. The average annual precipitation is 16 inches. The area has snow cover for about 5 months of the year.

Land use in the immediate vicinity of the mine is rural. The town of Magna (pop. 8600) is located 15 miles north of the site. Salt Lake City, a major metropolitan area, is located 20 miles northeast of the site.

The Bingham Canyon ore body is a typical porphyry or disseminated copper deposit that is centered in and around a complex monzonitic stock. Chalcopyrite is the principal copper mineral, although bornite also is common in the primary, instrusive ore zone and covellite, chalcocite, and other nonsulfide copper minerals are present in the zone of secondary enrichment. Surrounding the intrusive granite and the granite porphyry is a halo of mineralized quartzite that is characterized by a very high pyrite content.

The mine pit and leach and waste dumps border on two surface water drainages: Bingham Canyon and Butterfield Canyon. Surface runoff from these drainages flows east to the Jordan River, which feeds Utah Lake. The major water supply for the mine is from two wells in the intervening valley, about 3 miles east of the mine. The depth to ground water in these wells is 600 to 800 feet.

Design and Management Practices*

Under normal operations, low-grade ore (containing less than 0.4 percent recoverable copper) and barren waste rock are hauled from the pit by truck and deposited in segregated dumps constructed on bedrock. The low-grade ore is leached with a dilute solution of sulfuric acid, which is introduced to the dump surface by spraying (rainbird sprinklers). The pregnant liquor is collected at the base of the dumps in clay-lined ponds. The ponds were created by constructing concrete cutoff walls across natural drainages; these walls are keyed into bedrock to prevent subsurface losses. From the ponds, the pregnant liquor is conveyed via a main collection canal, which is constructed of epoxy-lined concrete, to the precipitate plant surge pond. The precipitate plant (largest in the world) contains 26 cones and operates on a continuous basis. After the copper has been recovered, the barren solution from the cones flows to a sump in the central pump station, from which it is pumped back onto the piles. The pH of this solution ranges from 2.5 to 3.0, hence makeup acid is not required.

Approximately 10 percent of the total area of the east dumps is leached at one time. A typical leach cycle is 60 days leach and 60 days rest. To minimize the buildup of iron precipitates on the surfaces of the dumps, the top 4 or 5 feet of material is ripped by a bulldozer after each rest cycle. After about two cycles, the top layer is scraped off and pushed over the edge of the dump.

*Because only the east side dumps are active, design and management practices relating to these dumps are described; see Figure 1.

Environmental Impact

Kennecott's east side collection system is "state-of-the-art." In addition to the main collection canal, a second, emergency overflow canal (also constructed of epoxy-lined concrete) collects excess stormwater runoff and conveys it to a 500-million-gallon overflow pond. This pond is partially lined with clay (i.e., the face of the dam and the bottom of the pond extending away from the dam for several feet are lined). This excess stormwater is treated with lime and discharged to a series of evaporation ponds. Site personnel have stated that this collection system does not contribute to existing ground-water contamination problems at the site.