

INTERFACING TECHNOLOGIES IN SOLUTION MINING

**PROCEEDINGS OF THE 2ND
SME-SPE INTERNATIONAL SOLUTION
MINING SYMPOSIUM
NOVEMBER 18-20, 1981**

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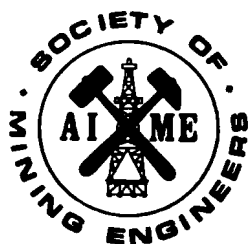
**PROCEEDINGS OF THE SECOND
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Editor

W. J. Schlitt

Associate Editor

J. B. Hiskey

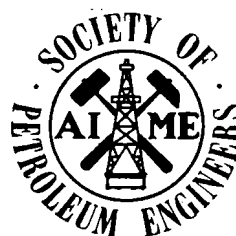


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PREFACE

The emergence of solution mining as an interdisciplinary technology has prompted both the Society of Mining Engineers (SME) and the Society of Petroleum Engineers (SPE) of AIME to actively address different aspects of this broad field. In order to promote an exchange of information between researchers and operators working in the various areas, the two societies have initiated periodic joint programming on solution mining. SPE had primary responsibility for the first symposium. This was held in 1980 as part of the SPE Fall Meeting in Dallas, Texas. Due to the short time available for developing the program, that meeting included only three joint sessions focussing on uranium solution mining. Although many of these papers found their way into SPE publications, a separate symposium proceedings volume was not issued.

Before the first joint meeting even took place, SME initiated efforts to organize the second symposium. This was scheduled as part of the 1981 SME Fall Meeting in Denver, Colorado. Since more time was available for this undertaking, a substantial effort was made to broaden the scope of the symposium and to encourage extensive foreign participation. The organizing committee took this charge seriously. Representatives of the Industrial Minerals, Mineral Processing, and Mining and Exploration Divisions of SME all joined with their SPE counterparts to help develop a comprehensive program on solution mining. The committee also adopted the theme, "Interfacing Technologies in Solution Mining" to reflect the interdisciplinary nature of the symposium.

The response to the committee's call for papers was overwhelming, with more than 60 abstracts submitted for possible inclusion in the program. In order to accommodate as many of these papers as possible, five technical sessions were scheduled. These covered trona, brine, and salt; copper, gold, and silver operations; uranium operations; advances in technology and the chemistry of solution-ore systems. In addition to the United States, papers were accepted from Australia, Canada, China, France, Netherlands, and Papua New Guinea. The foreign portion made up about a third of the program.

Ninety percent of the contributions were available in preprint form at the meeting. These manuscripts have been subjected to a peer review, careful editing, and indexing. They are included in this volume along with the papers which were not available at the meeting. In addition, the two papers on operations at Ortiz and Bulldog Mountain have been added to the proceedings volume. These could not be accommodated in the symposium due to limitations on each session. However, the papers were judged to be substantive in value. They were presented at the general SME meeting and warranted inclusion in the book.

The joint SME-SPE fall meetings compliment other AIME programming and publications on solution mining. Particularly noteworthy have been the annual uranium seminars sponsored by SME local sections. The series of minisymposiums and proceedings developed by the SME Solution Mining Unit Committee has also been significant. These symposiums have been held as part of each AIME Annual Meeting and have included the 1979 New Orleans sessions on in situ uranium mining and ground water restoration, the 1980 Las Vegas symposium on leaching and recovering copper, the 1981 Chicago sessions on gold and silver, and the 1982 Dallas symposium on solution treatment. The latter was cosponsored with the Mineral Processing Division's Chemical Processing Committee.

W. J. Schlitt
March 1, 1982

SYMPOSIUM ORGANIZING COMMITTEE

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William C. Larson, SME-Mining and Exploration Division

Bruce H. Mason, SME-Industrial Minerals Division

Erik I. Sandvik, SPE

Myles W. Scoggins, SPE

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Ruth M. Orologio, SME

Janelle Stewart, SPE

The organizing committee and the editors are most appreciative of the time and effort contributed by the authors in preparing their presentations and manuscripts. The editors would like to thank Myrna R. Anderson, Fred C. Dunford and Frances Hinkins of Kennecott Minerals Company and Marianne Snedeker of the Society of Mining Engineers for their efforts and support in preparing this volume. A special thanks also goes to Milton W. Wadsworth of the University of Utah who suggested the term "Interfacing Technologies in Solution Mining".

SYMPOSIUM SESSIONS AND CHAIRMEN

KEYNOTE SESSION

W. J. Schlitt, Kennecott Minerals Co., Salt Lake City, Utah

TRONA, BRINE AND SALT

B. H. Mason, The France Stone Co., Waterville, Ohio

ADVANCES IN TECHNOLOGY

L. W. Lake, The University of Texas at Austin, Austin, Texas

J. L. Shafer, Exxon Minerals Co., Houston, Texas

CHEMISTRY OF SOLUTION - ORE SYSTEMS

J. B. Hiskey, Kennecott Minerals Company, Salt Lake City, Utah

E. I. Sandvik, Exxon Production Research Co., Houston, Texas

COPPER, GOLD AND SILVER LEACHING OPERATIONS

R. H. Heinen, Dravo Engineers and Constructors, Denver, Colorado

D. A. Shock, Ponca City, Oklahoma

URANIUM LEACHING OPERATIONS

M. W. Scoggins, Nufuels Corp., Denver, Colorado

W. C. Larson, U.S. Department of the Interior,
Bureau of Mines, Minneapolis, Minnesota

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Chapter 1

PAST, PRESENT AND FUTURE OF SOLUTION MINING

**R. B. Bhappu
Mountain States Mineral Enterprise Inc.
Tucson, Arizona 85731**

ABSTRACT

Over the last decade, solution mining has emerged from its infancy into a technically and economically mature process for in situ extraction of selected commodities such as copper, uranium, gold, silver, and evaporites. Moreover, because of increasing labor and energy costs, environmental considerations, and decreasing ore grades, solution mining is destined to play an increasingly important role in the extraction of the above commodities as well as for others which are currently extracted by hydrometallurgical means. This paper traces the development of this versatile extraction technique, and as the keynote address, sets the stage for the technical papers on solution mining which make up the balance of the symposium program.

INTRODUCTION

In situ, chemical or solution mining is the in-place extraction of metals from ores located within the confines of a deposit or a mine (unfractured or fractured ore, stope fill, caved material, and ores in permeable zones), low-grade dumps, slag piles, and tailing ponds. These materials represent an enormous but untapped source of all types of metals.

It is inevitable that solution mining and in situ extraction concepts will be increasingly utilized in production of metals to satisfy the insatiable demands of our minerals-based society. This premise is based on reasonings such as ever increasing demand for today's metals, the necessity for treating complex and lower grade ores, increasing capital and operating costs, the need for conserving our dwindling mineral resources, and the public awareness of environmental problems associated with conventional mining practices. These factors necessitate the development of new techniques for extracting metals.

The overall scope of this potential mining method embraces interdisciplinary science and technology requiring application of principles of basic sciences, geo-sciences, bio-engineering, petroleum production, mining engineering, minerals extraction technology, and economics. The field of in situ mining encompasses the preparation of ore for subsequent in-place leaching, the flow of solutions and ionic species through rock masses and within rock pores, the leaching of minerals with inexpensive and regenerable leaching reagents under conditions prevailing in-place, the generation and regeneration of such solutions, and the recovery of metals or metal compounds from the metal-bearing solutions.

It is not inconceivable that eventually our ore reserves will consist largely of higher grade but deep seated deposits, low-grade zones near previously worked deposits, caved ore and stopes filled with submarginal ore, waste dumps, tailing ponds, and slag heaps. In situ mining promises economic recovery of metals from such sources.

Heretofore, this kind of mining has been more or less limited to the extraction of evaporites (trona, brine and salt), copper and uranium from lower-grade ores; however, it has a much greater potential. Practically all metals are susceptible to leaching in the in situ environment. Techniques will soon be developed for the in-place extraction and recovery of metals such as lead, zinc, nickel, manganese, silver, gold, molybdenum, and aluminum.

Historical

In situ leaching, though considered a modern technique, has been practiced since the last hundred years. Earliest patent coverage dates back to at least 1896. Copper dump leaching at the Rio Tinto Mines in Spain has been reported since the early part of this century. Cananea started leaching in place in the 1920's from mined out and caved underground stopes to extract residual copper from chalcocite ores using weak sulfuric acid solution containing ferric ions. Ohio Copper Company of Utah similarly started in situ leaching of mined out areas in 1942. In this case, stope pillars left between mined out veins were fragmented by blasting

to obtain a rubble area 1400 x 600 feet at the surface.

On the other hand, in situ extraction of uranium was initially conceived by Professor Livingston under U.S. Patent 2,818,240 titled "Method of Mining Ores In Situ by Leaching" in 1955. Utah Construction and Mining Company started in situ leaching of uranium in the Shirley Basin area of Wyoming around 1961 using the bore hole mining technique. Millike Mine of Rio Algom ceased underground mining operation in 1964 and converted to in situ leaching of uranium by washing down stopes with dilute acid solutions. The Stanrock Mine and Dennison Mines, located in the same district, also recovered uranium using a similar technique around 1965.

Twin Cities Mining Research Center of the United States Bureau of Mines [1] has compiled a detailed bibliography on in situ leaching technology.

TECHNOLOGICAL CONSIDERATIONS

Solution Mining Techniques

There are basically three distinct applications and associated leaching systems encountered in the field of solution mining, depending mainly in the physical location of the ore deposit. These situations are illustrated in Figure 1.

Typical examples of Type 1 are the numerous dump and heap leaching operations practiced by the open pit copper mines in the Southwestern United States. [2] Dump leaching, in general, is a convenience for open pit mining operations to dispose of lower grade (submarginal) stripped material in a remote area with the intention of recovering the valuable metals contained therein. Because of limited available area and easy placement, such dumps tend to be very high and the leaching of such piles, either through spraying or ponding of solution, is relatively slow and inefficient. Nevertheless, the production of copper from such dump and heap leaching operations at the present amounts to about 200,000 tons of copper per year in the United States or approximately 15% of the total production.

Heap leaching, on the other hand, is a system in which low grade or mixed oxide-sulfide ores are leached under controlled conditions in relatively small heaps on prepared pads or surfaces with positive drainage over a shorter leaching period. In some cases the ore is brought to permanent pads for treatment and removal, followed by piling of fresh ore on the same pads for treatment. Several successful heap leaching operations for extraction of copper, gold, and uranium are carried out in the U.S.A. It should be noted that the effectiveness of copper extraction in these dump and heap leaching operations has been partially attributed to bacterial oxidation of sulfide minerals.

Other viable in-place leaching situations belonging to Type 1 are the truly in situ leaching systems in which the ore is broken in-place by some type of blasting technique followed by percolation leaching of the fragmented ore mass. Appropriate collection galleries are provided to collect the leach solution for subsequent recovery of metal and recirculation of the barren solution for additional leaching. Since the ore is broken and left in place, such leaching systems are economically attractive.

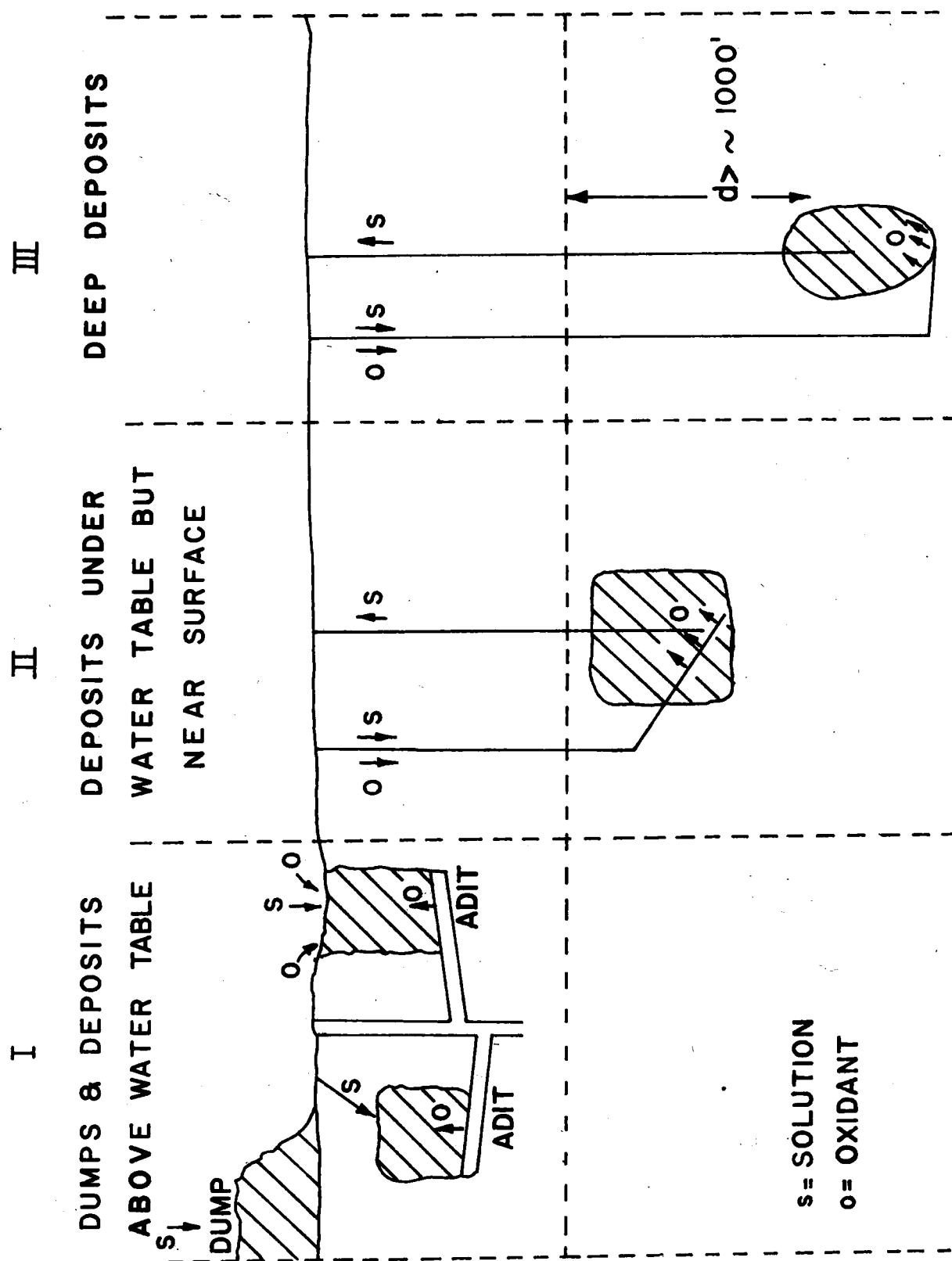


Figure 1 – Three types of in situ leaching situations. (According to Dr. Milton Wardsworth)

Ranchers Exploration and Development Corporation's Old Reliable Mine operation in Arizona and the Big Mike Mine in Nevada are fine examples of this in situ leaching method. [3-4]

Also, belonging to Type 1 are the classic in situ leaching operations of the Miami and Ray Mines, Arizona, U.S.A., in which the leaching has been carried out on fractured submarginal ore zones resulting from block caving operations. In the case of the Miami Mine operation, it has been estimated that 85,000 tons of copper metal have been produced over a 15 year period since completion of the underground mining operation in 1959, with an estimated recovery of about 60-70% of the metal left in place. The leaching operation continues with no decrease in recovery rate and no immediate end in sight. [5]

The second (Type 2) situation reflects the leaching of relatively shallow deposits located less than 300 meters from the surface and which are under the water table. Such deposits may need to be fractured in-place and the solution drained in order to commence the alternative leaching and drying cycles. Alternately, metal values from such deposits may be extracted by utilizing the bore hole mining technology as is currently practiced by uranium mining operations in the United States. The bore hole mining technique is also utilized for extraction of brines (salt and trona) and the modification of this system termed "slurry mining" may be used for mining phosphate rock, coal, uranium and copper ores.

The bore hole mining technique usually consists of a properly designed pattern of wells suitable for injection of the leaching solution and recovery of metal-bearing liquors. The wells are like water wells except that the casings are perforated for optimum leaching conditions. [6-8]

The final (Type 3) situations are characterized by relatively deep-seated deposits in excess of 300 meters and under the water table. Leaching of such copper deposits through chemical mining has been proposed by Lawrence Livermore Laboratory, University of California, U.S.A., after fracturing the ore body by nuclear devices. Leaching at such depths is enhanced by direct oxidation of sulfide minerals due to increased solubility of oxygen resulting from hydrostatic head. [9]

An alternate method proposed by University of Utah and Mountain States Research and Development for in situ extraction of deep seated copper deposits consists of effective rubblization through a modified block caving technique. In this case the required rubblization with about 8% porosity is achieved by employing conventional explosive to shatter the ore into a pattern of free space generated by mining appropriate lamellae every 100 feet of depth. Leaching would be carried out using modified bore hole mining technology with continuous oxidation provided by oxygen injection. [10]

A listing of various U.S.A. commercial and pilot plant operations employing the above three types of in-place leaching techniques in the extraction of copper, gold, and uranium are given in Table I. These examples of practical and economic operations clearly indicate that the in situ extraction technology has developed into a matured and a viable metal extract process.

TABLE I

IN SITU LEACHING PRACTICES IN THE U.S.A.

Dump Leaching

1. Several copper operations in Southwest U.S.A.

Heap Leaching

1. Bluebird Mine, Arizona (copper)
2. Inspiration Mine, Arizona (copper)
3. Johnson Camp Mine, Arizona (copper)
4. San Juan Mine, Arizona (copper)
5. Carlin and Cortez Gold Mines, Nevada (gold)
6. Round Mountain Mine, Nevada (gold)

In Situ Leaching (copper)

1. Miami, Arizona (block caving operation)
2. Ray, Arizona (block caving operation)
3. Mountain City, Nevada (block caving operation)
4. Old Reliable, Arizona (coyote blast)
5. Big Mike, Nevada (pit wall blast)
6. Zonia, Arizona (coyote blast)
7. Nuclear Blast (AEC - Kennecott concept for deep-seated deposits)
8. Kennecott's Experiment (near Safford, Arizona)
9. Occidental Mineral Co. (experiment at Miami, Arizona)

In Situ Leaching (uranium)

1. Utah Mining and Construction Company, Shirley Basin, Wyoming
2. Mine Water Leaching at Grants, New Mexico
3. Bacterial Leaching at Elliot Lake, Canada
4. Wyoming Minerals, Bruni, Texas
5. Wyoming Minerals, Ray Point, Texas
6. Arco-U.S. Steel-Dalco, George West, Texas
7. Union Carbide, Duval County, Texas
8. Exxon, Powder River Basin, Wyoming
9. Mobil Oil Corporation, Webb County, Texas

Advantages

1. In situ mining is environmentally more attractive, since it creates less surface disturbance and results in less water and air pollution.
2. In situ mining usually requires less capital and lower operating cost than a conventional mine and milling operation. Moreover, the total energy required in solution mining is much lower than that required to obtain the same quantity of metal by conventional processing methods.
3. In situ mining can often be used to recover metals economically from materials that could not be so treated by more conventional mining, milling, and smelting processes.
4. In situ mining increases a mine's ore sources and reserves. Low-grade or inaccessible ore zones, caved ore, and dumps and tailings may become ores, thereby

leading to more effective mineral utilization and conservation.

5. The leach solutions obtained through in situ mining usually lend themselves to a variety of metal recovery processes. The pure metal or metal compounds so obtained may be of greater value to a mine owner than the sulfide or oxide products normally obtained by conventional milling processes.
6. In situ mining can often be used in conjunction with a conventional mining or milling process to boost metal recoveries and increase ore reserves.

Disadvantages

1. Both physical and chemical restrictions may limit the usefulness of solution mining. The effectiveness of contacting ore with solutions and the recovery of leach solutions from the system without appreciable loss are two important physical factors. Dissolution or dissolution rates, metal precipitation, and solution regeneration chemistry are major factors.
2. Testing an in situ mining situation short of actual field operation sometimes proves difficult.
3. Ground water contamination may result from in situ mining operations.
4. Detailed information on the physical, chemical, and bacteriological factors involved in in situ extraction of metals and minerals has not been established commercially.

CONTROLLING PARAMETERS IN SOLUTION MINING

From a practical application viewpoint, the successful leaching of metals and minerals under in situ leaching environments is governed by several factors. These include elements of the leaching phase, geological and mineralogical considerations, solubility of minerals in various leaching reagents, effect of particle size, effective fragmentation, solution application and regeneration, and metal recovery methods.

Elements of the Leaching Phase

Accessibility, physicochemical interaction, and transport constitute the elements of the leaching phase involved in in-place extractions. Limitations imposed on any of these factors restrict the leaching process.

Accessibility is essential because interaction between the desired mineral and the lixiviant cannot take place in the absence of contacts, which depend on exposure and penetrability. The factors to consider are locations of the values, their volume and shape distribution, exposure area, specific surface, particle size, porosity, capillary pressure, viscosity, solubility of gases in leach solution, and surface roughness. Accessibility in most dump, heap and in situ situations also involves diffusion of lixiviant into ore fragments. This diffusion is governed by concentration gradient and

diffusivity, which in turn are influenced by particle size, micropore radius, temperature, and molecular mass.

Physicochemical interaction converts the desired constituents from a fixed to a mobile condition and is governed by the solubility of the solid in leach solutions, vapor pressure in gases, and the presence of bacteria. Knowledge of free energies of reactants and products helps to determine whether a reaction is possible. The kinetic factors involved include time, concentration, diffusivity, specific rate constants, wettability, and oxidizing conditions, especially due to bacteria activity.

The first two elements by themselves do not ensure successful leaching without transport of products away from and reactants to the zone of interaction through diffusion and convection. As discussed earlier, diffusion is controlled by concentration gradient and diffusivity. On the other hand, convective flow concerns interparticle penetration and is restricted by pressure gradient, permeability, viscosity, and surface roughness. In the case of oxide copper and uranium leaching, "sweep" zones (i.e., moving reaction boundaries) are important due to rapid chemical kinetics.

Role of Mineralogy

In the past, little attention has been given by both the geologists and mineral processing engineers to the geological and mineralogical occurrences which may be potential sources of leachable ores under in situ environments. On the one hand, geologists have devoted less attention to lower grade, complex mineral deposits, and therefore, may have inadvertently excluded such deposits as potential sources. On the other hand, the metallurgists have neglected to study in detail the geological environments and mineralization of potential ores with the view of determining the critical leaching that could assist in effective processing of these complex, sub-marginal deposits.

In the final analysis, a chemical processing technique converts the valuable metals to a mobile state under conditions similar to those which deposited them originally in the host rock. Thus, the relationship between ore-genesis and chemical processing is close when the process of mineral or metal deposition in a particular ore deposit is clearly understood. Phase equilibria studies, Eh-pH diagrams, solubility products, mineral chemistry, surface chemistry and thermodynamics are utilized more and more by processing engineers to selectively separate minerals, dissolve minerals, and recover valuable metals and by-products. Doubtless, many of the future advances in processing technology will be derived from improved understanding of ore-genesis and related geological sciences.

It is interesting to note that the effectiveness of in solution mining of copper, uranium, and gold by appropriate reagents is economically feasible because of favorable mineralization of the metal values in the host rock. This is especially true for successful leaching of oxidized gold ores at coarser sizes since these ores contain submicron size gold particles in fracture fillings and cavities in the host rock consisting of either limey or silicified siltstone, sandy dolomite, or schist. These host rocks also tend to be porous and remain

permeable throughout the leaching cycle. In the case of copper ores, the mineralization also occurs along macro and micro fractures in the host rock, while in the case of uranium, the values are in the form of secondary-enriched precipitates coating the sand grains in the sandstone host.

Solubility of Minerals

In general, nearly all the minerals are more or less soluble in either acids, alkalies, or other specific reagents such as cyanide. Most of the oxide-copper minerals such as azurite, malachite and chrysocolla are quite soluble in sulfuric acid. For this reason, sulfuric acid is the preferred leaching reagent for in situ extraction of oxide copper ores. However, in cases when the oxide copper ore contains considerable amounts of calcite (CaCO_3), the acid consumption is very high and it may not be economical to use sulfuric acid for leaching. Thus, the solubility of gangue contained in the ore may have profound influence in the selection of the appropriate reagent for leaching of valuable minerals.

As far as the sulfide copper minerals are concerned, simple sulfuric acid leaching is not very effective and the presence of $\text{Fe}_2(\text{SO}_4)_3$ is necessary to dissolve minerals such as chalcocite and chalcopyrite under in situ leaching conditions. The strong oxidizing conditions required for their dissolution are satisfied by the presence of ferric iron, and oxygen (air). Many commercial operations have failed because the required oxidizing conditions were not maintained during the leaching process. This is also the reason why the presence of oxidizing bacteria of the *Thiobacillus thiooxidans* is necessary in dump, heap, and in situ leaching operations. It should be noted that the required iron is either available in the natural ore or that it is added to the leach system through the cementation step in which copper from the leach solution is precipitated as elemental copper when the pregnant solution is contacted with scrap iron.

In the case of in-place leaching of uranium, both dilute sulfuric acid and carbonate-bicarbonate solutions are effective reagents for dissolving uranium minerals. However, both the reagents require a chemical oxidant to oxidize uranium from the insoluble +4 oxidation state to the soluble +6 state. Typical acid leach oxidants are NaClO_3 or MnO_2 and typical carbonate leach oxidants are hydrogen peroxide or NaOCl .

For gold and silver leaching, cyanide has been found to be the most selective reagent and is the universal solvent used. Here again, oxygen is required in the reaction and efforts must be made to maintain oxidizing conditions during the in-place leaching of gold and silver. [11]

Effect of Particle Size

Since leaching of minerals by various chemical reagents involves effective contact between the two, it is obvious that the mineral must be liberated or freed from the host rock. The only other way the reagent can contact the valuable mineral is by effective penetration or diffusion through fractures, cracks, capillary action, and other physical factors considered under the "elements of the leaching phase". Regardless of the process of contact, it is quite evident that the reduction in

particle size would be of considerable benefit in in situ leaching of metals and minerals. With finer ore size it would be possible to obtain higher extraction rates in shorter leaching periods.

Effective Fragmentation

The desired particle size in in situ leaching situations can be obtained through proper blasting and fracturing techniques. The blast design for in situ leaching closely follows the principles of blast design used in more conventional mining practices. However, in case of in situ blasting unusually large dimensions are involved and these pose inherent problems associated with large blasting situations. To date, several unusually large blasts have been made for leaching with results that are very encouraging. [12-15]

The important factors that need to be considered in engineering a blast for in situ leaching are (a) shape of deposit, (b) characteristics of ore body, (c) seismic activity encountered, (d) missile consideration, (e) type of explosive, (f) powder factor and distribution, (g) initiating and delay system, (h) loading logistics, (i) economics, and (j) safety.

Besides conventional fracturing by blasting compounds, efforts have been made to explore the possibility of using liquid explosives, hydrofracturing and nuclear explosives. No doubt these and many other new concepts for fracturing will be considered as in situ leaching becomes a more conventional method in the future. Because of environmental considerations, nuclear fracturing although proved to be quite effective, may not be applicable in the foreseeable future. Hydrofracturing, on the other hand, has shown considerable promise in limited applications, [16] and with additional effort may prove to be a versatile fragmentation technique.

Solution Application and Regeneration

The primary goals in solution mining are (1) to obtain maximum metal concentration in the minimum solution volume and (2) to recover a major portion of the leach solution fed to the system with an economic metal concentration over the life of the operation. This economic concentration should be such that the value of recovered metal will offset the cost of operation, amortization, overhead and profit. It is also important from environmental considerations that the leach solution be confined in the leaching system and not appear as a pollutant in ground water. This is especially important in gold and silver leaching using cyanide as the specific reagent. Both the toxic nature of cyanide and preciousness of leach solution containing gold and silver necessitates in-place leaching conditions approaching a "zero discharge" objective.

Inasmuch as the chemical reagents used in in-place leaching generally constitute a major cost item and greatly influence the economics of leaching, reagent generation and regeneration play a very important part in any solution mining process. Some reagents can be generated and regenerated by natural processes in the leaching cycle, whereas others are totally consumed and need to be replenished.

The only known example of auto-regeneration of reagent is the natural reactions involved in the

production of sulfuric acid and ferric sulfate from pyrite and spent ferrous sulfate solution under natural air or biological oxidation conditions. In some cases, part of the reagent is regenerated by the metal extraction process incorporated in the flowsheet, such as the regeneration of H_2SO_4 through solvent extraction and electro-winning as practiced in the extraction of copper from leach solutions. In other cases, though the regeneration of reagent from spent solutions is possible, it is not economically feasible or environmentally attractive such as the regeneration of cyanide from spent solution in gold leaching.

The Recovery of Metals from Leach Solutions

The final phase of any hydrometallurgical process, including solution mining, is the recovery of metals from leach liquors. Conventional purification of a metal-containing solution followed by recovery of metals or compounds from the solution either by chemical or electrolytic precipitation is employed to obtain the marketable product. These recovery techniques are adequately covered in the literature and their effectiveness is clearly demonstrated in several successful plant practices.

In connection with in situ leaching application, however, the recovery phase poses certain technical problems that may influence the overall effectiveness of the process. One such difficulty concerns treating a large volume of very dilute metal-bearing solution. This may require recirculation of the leach solution to build up the metal concentration followed by bleeding off a small part of the concentrated leach stream for metal recovery.

Newer techniques of ion exchange, solvent extraction, and charcoal adsorption are being used for effective concentration of metals from leach solution. Moreover, these procedures have proved very effective for processing large volumes of leach solutions containing more than one valuable metal. In recent years, the recovery of copper from leach solutions by solvent extraction-electrowinning has become more attractive than the copper cementation process used conventionally all over the world. Similarly, ion exchange has been exclusively used for recovery of low concentrations of uranium from in situ leaching operations. Finally, the use of activated carbon for the recovery of gold and silver values (as low as one part per million or less) from in-place leaching operations has become a favorite process. In this case, the precious metals are subsequently extracted by desorbing them from carbon by hot caustic-cyanide solution followed by electrolysis to obtain the dore.

ECONOMIC CONSIDERATIONS

From the economics viewpoint, the net return from a solution mining venture will depend upon the quantity and quality of metal or commodity extracted from the ore. The overall economics will also be influenced by the capital cost of unit processes such as cementation, solvent extraction, electro-winning and the like; the cost of utilities, supplies and reagents; and the prevailing prices of metals and by-products. Accordingly, it is imperative that realistic feasibility studies be carried out for any new solution mining venture in light of all these and many more influential factors.

It should be noted that feasibility studies play a very important role in evaluating solution mining projects since the percentage recovery of a metal under in situ leaching environment is very difficult to predict. The recoveries attained under actual operating conditions may not be as high as those indicated by laboratory or pilot plant tests. For this reason, it is customary in such feasibility studies to carry out cash flow analyses for a wide range of recovery levels (60 to 20%). If the cash flow does not appear to be favorable for 50 to 40 percent recovery levels, then it would be preferable to drop the project or undertake additional laboratory and field studies in order to increase the confidence level. On the other hand, if the cash flow looks favorable for 30 to 20 percent recovery levels, then the success of the venture is assured. Besides recovery levels, it is mandatory that cash flow analyses be made for varying metal prices since the economics of the venture is highly influenced by the price of metal or commodity.

In general, the net return from a mining venture such as in situ leaching depends on the quantity and quality of metal or compound extracted from the deposit. The overall economics is also dictated by the cost of exploration, capital costs of the unit operations involved in mining and extraction, the operating costs for labor, supervision, utilities and supplies; and on the prevailing price of metal and by-products. Accordingly, the economic feasibility of a solution mining venture must be accessed in light of all these and several other influencing factors.

The estimated capital costs of various unit processes encountered in typical solution mining operations for extraction of specified amounts of copper, gold and uranium are shown in Table II. On the other hand, Table III shows the estimated costs for different unit operations involved in extraction of the same commodities under in situ leaching extractions.

It is worth noting that in the case of copper, the cost of producing the metal by in situ leach-solvent extraction-electrowinning is considerably less than for cementation due to additional cost of smelting and refining (currently ranging from \$0.26-0.36 per pound) to produce high purity copper. On the other hand, for extraction of gold using the heap leaching-carbon adsorption-electrowinning concept, the direct cost of mining and processing is estimated to be less than \$5.00 per ton or less than \$7.50 including indirect, depreciation, etc. Accordingly, using this technique, it is currently feasible to process gold ores assaying 0.03 to 0.05 oz/ton if the gold price is \$400 per ounce.

Finally, for the extraction of uranium using the bore hole mining technology at a cost of \$17.50 to \$25.00 per pound of U_3O_8 extracted, it is feasible to work a uranium deposit averaging 0.05% U_3O_8 when the price of yellow cake is above \$25 per pound.

The effectiveness of in situ extraction of copper in comparison to conventional mining-milling-smelting-refining is clearly illustrated by comparing the operating costs as shown in Table IV. As can be seen, the overall cost per pound of copper produced by solution mining is in the range of \$0.45 to \$0.55 as compared to \$0.69 to \$0.88 for conventional method.