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In-Place Leaching of Uranium, Copper, and Evaporites

by T.G. Carnahan

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The purpose of this report is to discuss in-place leaching technology in the United States. Application of in-place leaching to uranium ores has been particularly successful. The sandstone ores are contained above and below by impermeable shales and the uranium ore minerals are easily leached with oxidizing acid or base solutions. Copper is recovered from subgrade rock by dump or in-place leaching with acidified ferric sulfate solutions. The leaching solution migrates down through the rock and dissolves copper. The solution is collected from the base of the dumps and copper is recovered by solvent extraction, electrowinning, or by cementation on detinned steel cans. Solution mining of evaporites is being conducted commercially for the extraction of sodium chloride and potassium chloride.

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IN-PLACE LEACHING OF URANIUM, COPPER, AND EVAPORITES

by

T. G. Carnahan[1]

ABSTRACT

In-place leaching is being actively utilized to extract uranium, copper, and evaporites from low-grade and difficult-to-mine ores. The purpose of this report is to discuss in-place leaching technology, its advantages and disadvantages, and to give an overview of past, current, and envisioned in-place leaching operations in the U.S.A. Application of in-place leaching to uranium ores has been particularly successful because the conditions for leaching are nearly ideal. The ores are generally in highly permeable sandstone aquifers bounded above and below by impermeable shales. The uranium ore minerals are easily leached with oxidizing acid or base solution and the pregnant solutions are amenable to ion exchange concentration and purification prior to conventional solution neutralization for recovery of yellow cake.

Copper is routinely recovered from sub-grade rock by dump leaching at most major copper mines. Acidified ferric sulfate is either sprayed on the surface of the dumps or is ponded on top of the dumps. The leaching solution migrates down through the rock and dissolves copper. The solution is collected from the base of the dumps and copper is recovered by solvent extraction-electrowinning or by cementation on detinned steel cans. True in-place copper leaching is being practiced in the caved stopes of an exhausted underground copper mine. Other innovative in-place copper leaching techniques have been tested commercially and laboratory- and pilot-scale experiments have been conducted to investigate proposed in-place leaching techniques for extracting copper from difficult-to-treat chalcopyrite ores.

Solution mining of evaporites is being conducted commercially for the extraction of sodium chloride and potassium chloride. A large-scale experimental project for solution mining of trona has been undertaken.

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[1] Metallurgist, Reno Research Center, Bureau of Mines, Reno, Nev.

INTRODUCTION

There is substantial commercial interest in the U.S.A. in recovering metal values by leaching ore deposits in place (1,6, 10,14-15,21,27-28,34,39,43-44,47,57,59-60.[2] Leaching in place entails delivering a solvent solution to the deposit, providing means for the solvent solution to move throughout the ore to dissolve the values from the ore, and providing for solution recovery and processing facilities. Uranium, copper, and evaporite deposits have been successfully exploited by in-place leaching technology. Two major bibliographies were compiled that adequately reference the in-place leaching literature (16,28).

The purpose of this report is to discuss in-place leaching techniques, their advantages and disadvantages, and to give an overview of past, current, and envisioned in-place leaching operations in the U.S.A.

A variety of in-place leaching techniques have been used. These include:

- Leaching a permeable deposit in place.
- Leaching of sub-grade dumps.
- Leaching of sub-grade rock surrounding mined-out areas.
- Solution mining of evaporite deposits.

When leaching a permeable deposit in place, wells are drilled into the ore to the impermeable base rock of the deposit. Leaching solution flows from injection wells through the ore to the recovery wells. More solution is pumped from the deposit than is injected in order to prevent leach solution from escaping from the deposit. Leaching occurs as the solution passes through the ore. Pregnant solution is pumped to the surface and processed in a recovery plant. The necessary makeup chemicals are added and the solution is reinjected to continue the leaching. Dump leaching is conducted on waste piles containing sub-grade concentrations of the commodity

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[2] Underlined numbers in parentheses refer to the list of references at the end of this report.

being mined. The leaching solution is sprayed onto the surface of the dump, ponded on top of the dump, or injected into wells drilled into the dump. The leaching solution migrates through the dump and dissolves the metal values. The pregnant solution is collected from the base of the dump and pumped to the recovery plant. The solution is reapplied to the dump after the necessary makeup chemicals have been added. Leaching sub-grade rock surrounding mined-out areas is done by drilling wells to just above the workings. The leaching solution is injected into the wells, migrates through the rock and collects at the bottom of the workings. It is pumped to the surface for processing, reagent replenishment, and reinjection. Massive evaporite deposits are worked by injecting water into the deposit. A cavern forms as the salt is dissolved. The salt-saturated solution is pumped to the surface for crystallization and purification or for direct use.

In-place leaching has a number of potential advantages over conventional mining and milling procedures (7,22-24,51-52, 61). The advantages include:

- Lower energy requirements.
- Lower capital investment.
- Minimal permanent land disturbance.
- Less long-term pollution potential.
- High product output per employee.
- Extremely low safety hazard.
- Shorter lead time before production.

Because the ore remains in place and is not crushed or ground, the energy requirements are small (45). Elimination of crushing, grinding, and beneficiation equipment decreases the capital investment of the project. The landscape remains unspoiled because there are no open pits, waste dumps, or tailing ponds associated with in-place leaching. Absence of these structures eliminates the long-term potential for air pollution due to wind erosion and water pollution due to precipitation seeping through the mined area. Productivity is high because most operations are easily automated and there is no labor intensive mining involved. In-place leaching is inherently safe because the danger of ore handling is eliminated, no high temperatures are involved, and a minimal amount of mechanical equipment is employed. Miners are not exposed to underground radiation hazards. Simpler processing facilities and no need for overburden stripping result in shorter lead times before production begins.

In-place leaching also has potential disadvantages when compared to conventional mining-milling practice. The disadvantages include:

- Lower metal recovery.
- Lower accessory element recovery.
- Long extraction times.

In most cases, the metal recovery will be lower because not all of the ore mineral particles are exposed to the leaching solution. Because many are encased in gangue, the leaching solution must diffuse through a layer of rock to the mineral particle, react, and then transport the dissolved metal species back through the rock to the surrounding solution. Consequently, the extraction efficiency of in-place leaching is usually less than the 80 to 95 pct for conventional mining-milling practice. The second potential problem of in-place leaching, poor accessory element recovery, can be a major concern. The state of the art currently is to recover only the major element of interest. In the case of uranium, vanadium is often present in the ore. Vanadium is not recovered during in-place leaching of uranium. Copper is even more critical. Approximately 40 pct of the U.S. silver, gold, and molybdenum production comes from copper concentrates. Leaching systems currently envisioned for copper ores would recover only a small fraction of these metals. The third disadvantage, long extraction time, can be particularly troublesome for hard, impermeable deposits. This is compensated to some extent by the decreased time necessary to bring an in-place leaching project into production.

In-place leaching projects that have been initiated have been in situations where the advantages are maximized and the disadvantages are minimized. The non-evaporite projects have primarily been on small, easily leached uranium deposits and small, easily leached, near surface copper deposits. As in-place technology matures and new leaching systems capable of extracting primary and accessory elements from hard, impermeable deposits are developed, the larger, deeper, multi-metal deposits will be leached in place.

IN-PLACE LEACHING OF URANIUM

Within the last 7 years, in-place leaching of uranium has become proven technology in the uranium industry. There have been as many as 14 commercial in-place leaching plants producing more than 3.3 million pounds of U_3O_8/year. Five more plants are under construction (60).

United States uranium ores are amenable to in-place leaching methods because the host rock is usually a permeable sandstone which is ideal for percolation of leaching solutions. Because the deposits are small and often below the water table, containment of the leaching solutions is feasible. Deposits are buried at depths up to 900 feet and give operators the choice of costly open pit or underground mining or less costly in-place leaching.

In-place leaching applied to uranium ores usually consists of patterns of wells for introduction of leaching solutions into the ore body and their recovery (7,19,27,50). The wells are similar to water wells except that they are cased with material resistant to attack by the leaching solutions.

In-place leaching of uranium can be discussed in terms of four basic operations--leaching, concentration-purification, neutralization, and yellow cake recovery. Leaching solution is injected and recovered from the ore body in the leaching step. Uranium is extracted from the leaching solution by ion exchange and elution from the resin with a strong chloride solution.

The concentrated uranium solution is acidified, if necessary, and then neutralized with ammonia in order to precipitate yellow cake. Yellow cake, a combination of uranium oxides and ammonium diuranates, is recovered by conventional liquid-solid separation techniques.

Scope of In-Place Leaching in the Uranium Industry

Water from underground mines near Grants, N. Mex., is being injected into the areas above worked-out stopes (fig. 1). The water containing about 1/2 gram of HCO_3^-/1 and oxygen from the mine solubilize the uranium in the low-grade margins of the stopes. Mine water is injected, collected, and recycled until the U_3O_8 concentration is about 15 ppm. This solution is sent through ion exchange columns to recover the uranium values. Production of 5,000 to 10,000 lb of U_3O_8 per month is achieved at minimal expense.

Heap leaching is a means for treating low-grade ore (38,53). Graded, compacted, slightly sloping bases are prepared (fig. 2). Plastic sheeting is laid down and covered with fine gravel. The gravel cushions the base so that trucks can drive over it and dump waste ore without destroying the plastic sheeting. Perforated plastic pipes are buried in the fine gravel to collect pregnant effluent and direct it to collection

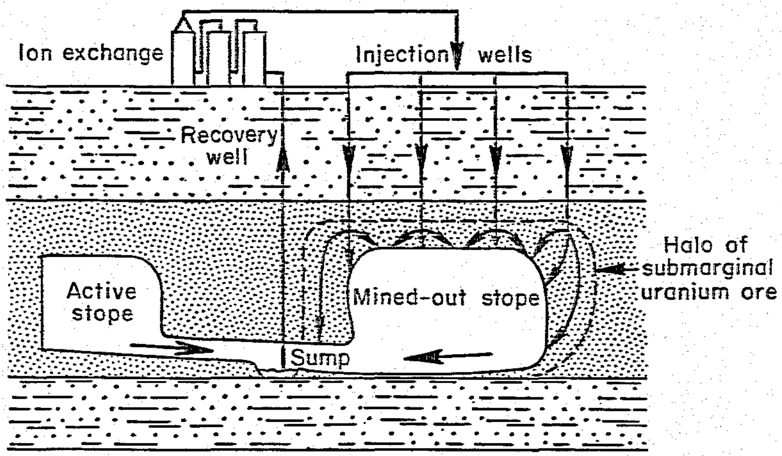

FIGURE 1. - Vertical section of injection leaching of mined-out stope with ground water.

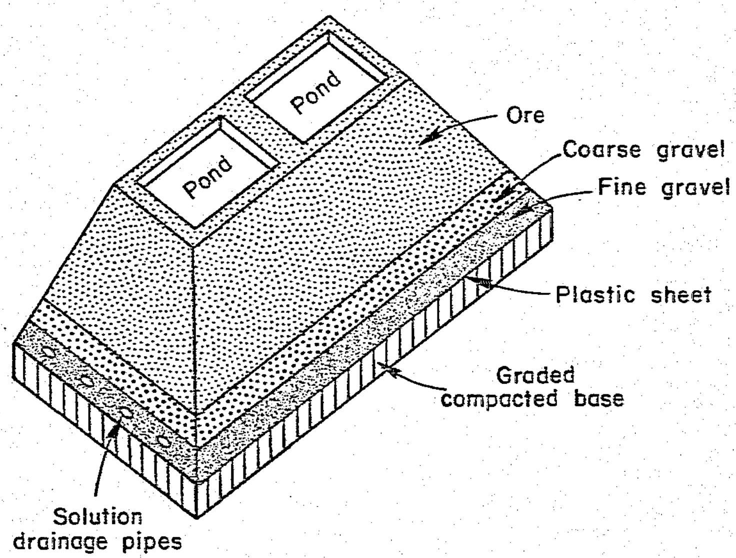

FIGURE 2. - Schematic drawing of a heap of low-grade uranium ore.

ponds. Heaps are built 20- to 50-ft high and up to 300- to 400-ft long. A berm may be built on top of the heaps for pond leaching or the heaps may be wetted with sprinklers. Bacteria assist the leaching process if there is good aeration. Effluent may be treated by ion exchange or sent to the mill depending on its location relative to the waste ore. Recoveries of 80 to 90 pct have been obtained in 16 months of leaching although 50 to 70 pct are more common. The lower extractions are due to poor oxidation or solution channeling within the heaps. Ores containing significant amounts of clays are not amenable to heap leaching because of slow percolation rates and heap instability problems. However, a new ore preparation technique developed by the Federal Bureau of Mines promises to eliminate these problems and permit exploitation of these resources (20,35). The technique involves agglomerating the ore with portland cement or sodium silicate binders before leaching. The agglomerated ore is permeable and heap instability problems are eliminated.

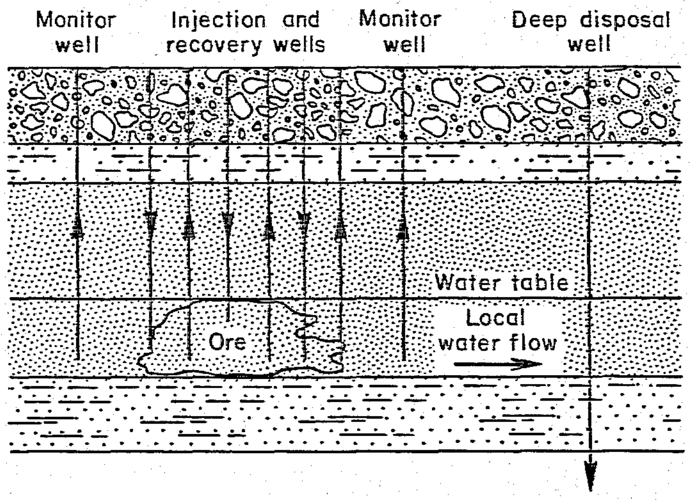

FIGURE 3. - Vertical section of in-place leaching system showing monitor, injection, recovery, and deep disposal wells.

True in-place leaching (fig. 3) was practiced as early as 1961. In-place operations are typified by Mobil's 650,000 lb/year in-place leaching project in south Texas which has a 20-year life expectancy (6). The company is leaching 11 acres of ore at 300- to 900-ft depth with a carbonate-dissolved oxygen leachant. Wells are located on 70-ft square grids with groupings of one recovery and four injection wells.

Geomorphology of Uranium Deposits

Many United States uranium deposits are of the so-called roll front type (25) that formed when uranium migrated in ground water through the host sandstone formation until it encountered a reducing zone and precipitated as a coating on the sand grains. Uranium minerals common to these deposits are the oxide, uraninite - $(U_{1-x}^{4+}, U_x^{6+})O_{2+x}$, the silicate, coffinite - $U(SiO_4)_{1-x}(OH)_{4x}$, and the uranium-vanadium oxide, carnotite - $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$. Typically, roll front deposits are narrow in width and stretch along a distance many times the width or thickness. Ore bodies range in size from 10,000 to millions of tons. A roll front configuration (fig. 4) consists of an interface separating sandstone

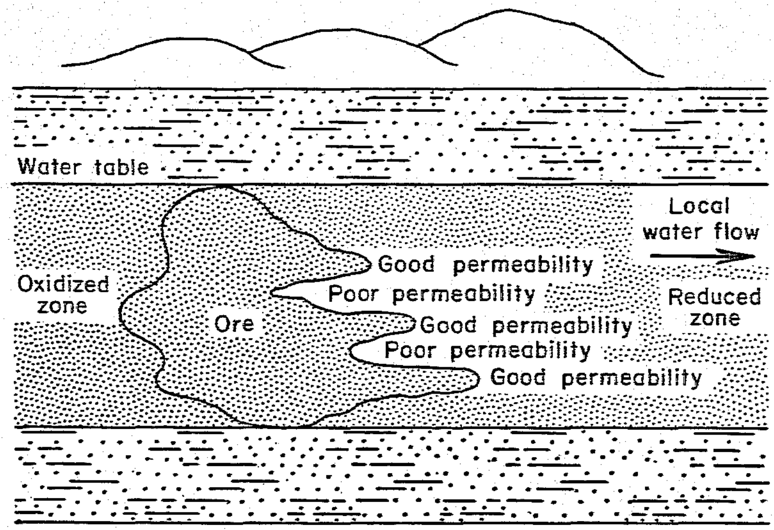

FIGURE 4. - Vertical section of roll front uranium ore body.

containing oxidized minerals from sandstone containing reduced minerals (pyrite, uraninite, etc.). Reductants include carbonaceous matter, H_2S, pyrite, etc. Often the roll configuration is complex because the sandstone aquifer in the mineralized zone will contain clay-rich intervals that act as permeability barriers and split the sandstone into thin parallel transmissive zones.

Mineralization is localized between the oxidized and reduced zones. Uranium content along the oxidized-reduced interface is variable but decreases gradually in either direction away from the center. Thickness of the roll front also diminishes away from the center. Therefore, sufficient drilling has to be done to establish parameters, such as ore grade, permeability, type of host rock, and ground water flow, before considering a deposit for in-place leaching.

Uranium deposits also occur in buried stream channels containing a reductant. The irregularities of the deposits are as complex as roll front deposits because of variations in permeability of the sands and reductant supply.

Leaching Processes

Two leaching procedures which are effective for extraction of uranium from its ores are dilute sulfuric acid and carbonate-bicarbonate leaching (38). Both systems require a chemical oxidant to oxidize uranium from the relatively insoluble 4+ oxidation state to the soluble 6+ state. Acid leaching oxidants are usually ClO_3^- or MnO_2, whereas oxygen, H_2O_2, MnO_4^-, or OCl^- can be used with carbonate leach solutions. Leaching reactions are as follows:

Acid

$$1/3NaClO_3 + 2FeSO_4 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 1/3NaCl + H_2O \quad (1)$$

$$UO_2 + Fe_2(SO_4)_3 + H_2O \rightarrow UO_3 + 2FeSO_4 + H_2SO_4 \quad (2)$$

$$UO_3 + H_2SO_4 \rightarrow UO_2SO_4 + H_2O \quad (3)$$

$$UO_2SO_4 + SO_4^{2-} \rightarrow UO_2(SO_4)_2^{2-} \quad (4)$$

$$UO_2(SO_4)_2^{2-} + SO_4^{2-} \rightarrow UO_2(SO_4)_3^{4-} \quad (5)$$

Carbonate

$$UO_2 + 1/2\ O_2 \rightarrow UO_3 \quad (6)$$

$$UO_3 + CO_3^{2-} + 2HCO_3^- \rightarrow UO_2(CO_3)_3^{4-} + H_2O \quad (7)$$

For acid leaching, the chemical oxidant oxidizes ferrous iron to the ferric state. Ferric iron oxidizes the uranium to the 6+ state. The solution oxidation potential must be maintained more negative than -400 mV, measured with platinum and saturated calomel electrodes, to attain reasonable leaching rates.

Acid leaching is used extensively in conventional milling because the process is cheap and more effective than carbonate for extracting uranium in a short time. The chief acid consumer is calcium carbonate which reacts according to

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + CO_2 + H_2O. \quad (8)$$

$CaSO_4$ is only soluble to the extent of 1/2 gram of Ca/l. Therefore, H_2SO_4 leachants for in-place leaching must be used with care or the ore body will be blinded by gypsum precipitation. Ore was successfully leached in place with acid strengths of 1.0 to 1.5 g/l until the pH began decreasing at the recovery wells and indicated that most of the lime had reacted and was being washed from the ore. Acid strength was then increased to 5 g/l with no plugging problems (1).

Carbonate leaching is used almost exclusively for in-place leaching in the U.S. because it is more specific for uranium and has less reaction with gangue minerals. These process characteristics permit leaching only exposed uranium minerals. Consequently, diffusion controls leaching and gives a slow leaching rate. Either acid or carbonate solutions can react with clays and cause swelling that results in plugging or decreased permeability of the ore body (23,42,54).

Conditions for Successful Application of In-Place Leaching

The high permeability and good leachability of uranium ores makes them candidates for in-place leaching. Once an ore has been declared a candidate for in-place leaching, it must satisfy certain in-place leaching criteria. First, the ore body must lie below the water table and between relatively impervious strata. Most uranium ore bodies in the U.S. were formed under these conditions. A filled reservoir is necessary for leaching solution to be contained. If the ore body were above the water table, capillary movement would be unavoidable and leaching solutions would migrate around and past the recovery wells. Filled reservoirs can be pumped at a slightly greater rate than leaching solutions are injected (fig. 5) and result in complete recovery of leaching solutions. Impervious strata above and below the ore-bearing formation prevent leaching solutions from escaping upward or downward. Vertical anisotropy of permeability due to layering also assists in retaining solutions to the planes of injection.

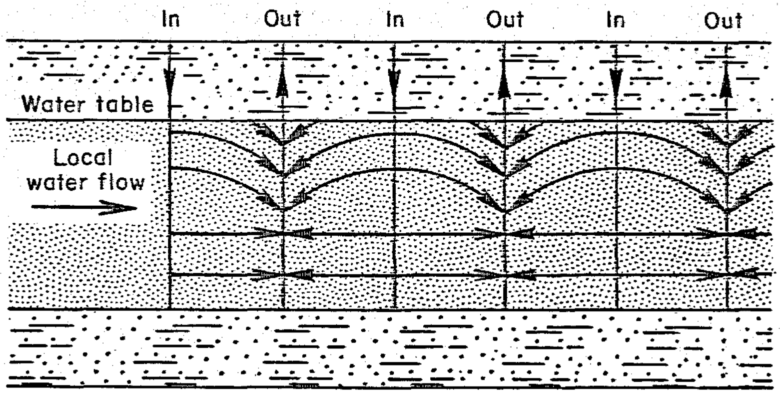

FIGURE 5. - Vertical section of ore body containing injection and recovery wells and showing flow patterns of leaching solutions.

The nature of the ore body and enveloping strata and the mineralization of the ore must be determined by extensive core drilling, searches of published literature, and on-site geologic survey. The ore body must not contain major faults or fractures that would cause short circuiting of leaching solutions. Hydrologic data from the survey should be studied to provide baseline information on ground water quality and the flow rate and direction of flow of the ground water. The ore body must be amenable to percolation leaching. Initial extraction tests are run on ground ore samples to determine their amenability to acid or carbonate leaching and to optimize leaching solution and oxidant requirements. Reaction products, such as reducing gases or gypsum, that could cause increased reagent consumption or blind the ore body are observed and noted. Core samples are tested for permeability and porosity by American Petroleum Institute standard tests to determine the ranges to be expected in the ore. Core samples are leached to develop extraction rate data. Estimates of the permeability during leaching are made to determine if the ore body may tend to plug due to reaction of gangue constituents with the leachant or by movement of clays if present.

Once a property has been declared viable for in-place leaching based on geologic, hydrologic, and metallurgical amenability, a pilot leaching program is undertaken and may or may not include solution processing. The purpose of pilot leaching is to develop reagent consumption data and competence in well construction, solution injection, well pattern design, and aquifer restoration. An indication of the percent recovery to be expected and of unexpected problems to be solved before construction of an actual operating plant are obtained.

Health, Safety, and Land Rehabilitation

In-place leaching generates no tailings but generates liquid effluents because more solution is recovered than injected. Sealed surface-evaporation ponds and deep well disposal into strata containing non-potable waters are being used to dispose of the water. Because the word uranium arouses negative public opinion, regulations require that a major effort be made to monitor possible leakage of uranium-bearing solutions from the in-place leaching area. Monitor wells surrounding the leaching area, in the leaching area, and above the leaching zone are necessary to sample the water before and during the life of the project. The public should be informed that a water sampling program is in effect. Since in-place leaching involves no mining, the dangers of underground or open pit mining are eliminated and the hazards of inhalation of radon gas are decreased.

When the ore body has been completely leached, all residual leaching solution must be washed out of the formation and conditions that were present before leaching reestablished.

IN-PLACE LEACHING OF COPPER

In-place leaching of copper is a much more difficult problem than in-place leaching of uranium. The gangue in copper deposits is usually granodiorite or similar hard, impermeable rock and some of the copper minerals are not readily soluble. As a result, commercialization of in-place leaching of copper has not been as extensive as for uranium. Deposits that have been successfully leached in place have been small and/or near to the surface. Dump leaching of low-grade waste, which is practiced at nearly every major copper mine, contributes approximately 10 pct of the U.S. primary copper production (33,37).

With the exception of dump leaching, the technique used to extract copper is always unique to the deposit. Nevertheless, all hard rock copper deposits must have the copper mineralization located primarily along a well-defined network of interconnecting veins or filling fractures before leaching can be successful.

A second requirement for successful leaching is fracturing of the ore to expose the copper minerals to the leaching solution and to permit migration of the leaching solution through the deposit. Surface deposits have been rubblized by huge explosive blasts (44). Deeper deposits have been block caved or hydrofractured with high pressure water to fracture the ore (17,43).

The deposit must have copper minerals that leach at a reasonable rate. Oxide copper minerals and chalcocite have favorable leaching rates in the acid leach systems that have been employed (55). Chalcopyrite leaching kinetics are too slow (12,56).

Chemistry

Most copper in-place leaching projects have utilized sulfuric acid because of its ready availability, its low price, and the fact that oxidation of sulfides produces sulfate which would be a contaminant in a non-sulfuric acid leaching system. An oxidant is needed for copper sulfide ores. Ferric sulfate is the usual oxidant because the iron is obtained from the reaction of the acid with iron minerals in the ore. Typical leaching reactions for common copper minerals are:

Chalcopyrite

$$CuFeS_2 + 2Fe_2(SO_4)_3 \rightarrow CuSO_4 + 5FeSO_4 + 2S^\circ \qquad (9)$$

Chalcocite

$$Cu_2S + Fe_2(SO_4)_3 \rightarrow CuSO_4 + CuS + 2FeSO_4 \qquad (10)$$

Covellite

$$CuS + Fe_2(SO_4)_3 \rightarrow CuSO_4 + 2FeSO_4 + S^\circ \qquad (11)$$

Malachite

$$CuCO_3 \cdot Cu(OH)_2 + 2H_2SO_4 \rightarrow 2CuSO_4 + CO_2 + 3H_2O \qquad (12)$$

Effective leaching of copper sulfide minerals requires continual regeneration of ferric sulfate as follows,

$$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O \qquad (13)$$

After the copper has been solubilized, its recovery is by one of two methods. Either an impure copper is recovered by cementation on detinned steel cans or a high-purity copper is recovered by solvent extraction-electrowinning (36). In either case, the solution after copper recovery is recycled to the ore for continued leaching.

Techniques and Applications

A significant metallurgical development in the U.S. copper mining industry during the past 25 years has been the rapid expansion of copper production through dump leaching of copper-bearing mine wastes. Major copper deposits which are mined by open pit methods consist of a core of ore which is mined for concentration. In the zone surrounding the central core, the copper mineralization decreases. As the mining pit becomes deeper, more of the peripheral material must be removed to maintain safe working conditions. This material, although not devoid of copper, must be moved to waste dumps. Because most major open pit mines in the western United States are producing sulfide ores, the waste dumps contain principally low-grade sulfide mineralization.

Dumps require very little capital investment and are economical to operate. The metal extraction is slow and the recovery is low because of poor oxidation of the sulfide minerals. As in uranium heap leaching, the leaching solution is applied by spraying or by ponding. The solution percolates through the dump and collects in a sump at the base of the dump. Copper is removed from the solution, and the solution is recycled to the dump. Most copper dump leaching operations achieve 40- to 60-pct copper extraction in 5 years (33).

Closely related to dump leaching is heap leaching (2,48). Two major heap leaching operations have been conducted at the Bluebird and Johnson Camp mines in Arizona (46,49). The major difference between dump and heap leaching is that the former is a scavenging operation, whereas the latter is a primary copper extraction operation. Higher grade ore is leached and more care is taken to assure that solution percolates uniformly through the heaps. Solvent extraction is employed to minimize iron buildup in the recycled leaching solutions.

A clever variation of heap leaching was the Big Mike in-place leaching project near Winnemucca, Nev. (58). Part of the wall of a small open pit copper mine was blasted into the pit. Approximately 600,000 tons of mixed copper oxide-sulfide bearing rock was fractured. Leach solution was sprinkled over the terraced surface of the ore, it percolated down through the ore rubble, and it was recovered by pumping through a single 160-ft-deep stainless steel cased well located in the center of the leaching area. Ground water prevented the leach solution from escaping. Copper was recovered by cementation. The barren leaching solution was recycled after adding H_2SO_4 to adjust the solution pH.

True in-place leaching has been practiced in the caved stopes of a former underground mine at Miami, Ariz., since 1941 (17). Dilute sulfuric acid solution is injected into the overburden and trickles through the block-caved oxide-chalcocite-bearing rock. The solution collects in a sump at the base of the treatment zone and is pumped to a solvent extraction-electrowinning plant for copper recovery. The barren solution adjusted to the required acid strength is reinjected into the ore. A refinement of this technique was employed at the Cliffs copper mine near Mountain City, Nev. (9). Block caving was used to mine 11 pct of the ore from the base of the deposit. The mined ore was placed on a prepared impervious pad and heap leached. The block-caved ore was leached as described in the preceeding discussion.

Copper has been recovered commercially from two oxidized deposits that were fractured in place by chemical explosives. The Old Reliable deposit near Mammoth, Ariz., was terraced after fracturing and leached with dilute sulfuric acid (57). The solution percolated through the ore by gravity. Copper-bearing pregnant solution emerged at the bottom of the fragmented deposit. Copper was removed from solution by cementation. The Zonia surface deposit in Arizona was fragmented, and recovery wells were drilled to the bottom of the fragmented zone and cased (44). Acid solution was sprayed on the rubble, percolated down through the ore by gravity, and was recovered by pumping from the recovery wells. Copper was extracted from the solution by cementation.

A large oxidized copper deposit located beneath the town of Miami, Ariz., was tested for in-place leaching (43). Preliminary results from a 5-spot well system after hydrofracturing were encouraging. The company also tested a 9-spot well pattern to assess the feasibility of scaled-up operations. The proposed leaching method involved sinking a shaft outside of the town. Drifts would be driven under the town and wells would be drilled into the deposit from the drifts. The deposit cannot be exploited by means other than in-place leaching because it is located beneath the town.

The hydrofracture-in-place concept has been tested in a deep deposit (14). A 5-spot well pattern was drilled to a depth of 5,000 ft in a difficult to mine portion of Kennecott's Safford, Ariz., deposit. Although the results of the test are proprietary, the experiment was significant because it was conducted at a considerable depth.

Low copper extractions have precluded commercial application of in-place leaching chalcopyrite and native copper ores. Laboratory experiments at the Bureau of Mines and elsewhere have been addressed to the problem (3-5,8,13,29-32, 36,40). The research has shown that oxidizing acid solutions, such as dilute nitric, nitric-sulfuric, oxygen or air-sulfuric, oxygen or air-hydrochloric, chlorine-hydrochloric, or ferric chloride or sulfate and basic solutions of oxygen or air-ammonia are capable of oxidizing chalcopyrite (56). The oxygen-ammonia system is also applicable to native copper ores (36). Most research on in-place leaching of chalcopyrite ore has been conducted with the oxygen-sulfuric acid system because some sulfuric acid is produced during oxidation of sulfide minerals in the ore. This acid is utilized in the leaching process and decreases the amount of acid required to leach the ore. Ammonia-oxygen systems have been investigated when basic gangue constituents are present in the ore.

In-place leaching research on chalcopyrite ore has been scaled up by Braun, et al. (4) to tests involving more than 6 tons of minus 6-in ore. These experiments were conducted for a time period of at least 700 days with sulfate solutions at 90° C. Oxygen at 400 psig was bubbled through the solution. No acid was added to the solutions because oxidation of the sulfides was sufficient to maintain the pH of the solution at 1.95. The copper extraction rate was parabolic during the first stage of the experiment and linear thereafter. Overall copper extraction was more than 45 pct. Research showed that the water-oxygen system for in-place leaching was technically feasible but required long leaching cycles to achieve good extractions.

Other research has shown that copper is removed from solution by ion exchange with clay alteration products in the ore when the leaching temperature exceeds 100° C and/or when the copper concentration in solution is allowed to build up (8,26,29).

Northern Michigan is reported to have the largest inferred reserve of copper ore in the United States (3 billion tons of 0.9-pct copper ore). The mines are closed because of high costs associated with mining the deep deposits. As a result of the past mining activity, there are many stopes filled with broken low-grade copper ore. The Bureau of Mines (36) conducted a tonnage-scale simulated in-place leaching experiment on minus 12-in conglomerate-type native copper ore using dilute ammoniacal-ammonium carbonate solutions under low oxygen pressure. The leaching solution contained 2.2 grams of NH_3/l and 1.9 grams of CO_3^{2-}/l. A total of 63 pct of the copper was leached from the ore in 550 days. The experiment established that this leaching approach is technically feasible.

As copper ore grades in the major near-surface conventionally mined deposits decrease, in-place leaching will become a competitive alternative extraction technique. Technology that enables more rapid copper extraction and recovery of the accessory elements contained in the ore will enhance the commercialization of in-place leaching.

EVAPORITES

In-place leaching of evaporite deposits is termed solution mining rather than in-place leaching because there is no chemical oxidation or reduction occurring between the solvent and the ore minerals, and because of the massive nature of the deposits. The majority of the material in the deposit is solubilized by the leaching solution. Solution mining of salt (NaCl) is the oldest and the largest tonnage in-place extraction application in the United States. Two types of deposits, salt domes and layered or "bedded" deposits, are being exploited (41).

Solution mining of salt deposits has been conducted in the United States since 1877. More than 50 pct of the U.S. salt production is obtained by solution mining (18), amounting to approximately 24 million tons per year.

The determining factors in the choice to solution mine a salt deposit instead of dry mining are the geological nature and the depth of the deposit, and the location and nature of the immediate downstream use of the product. Compared with dry mining, its economic advantage generally increases as the depth to the deposit increases. Solution mining is economically suited to fill needs that either require or permit the use of salt in solution. Consequently, the chlor-alkali industry consumes most of the salt produced by solution mining.

The essentials of solution mining a salt dome are shown in figure 6. This arrangement can be used on bedded salt deposits of sufficient thickness. Oilfield practice is followed in the

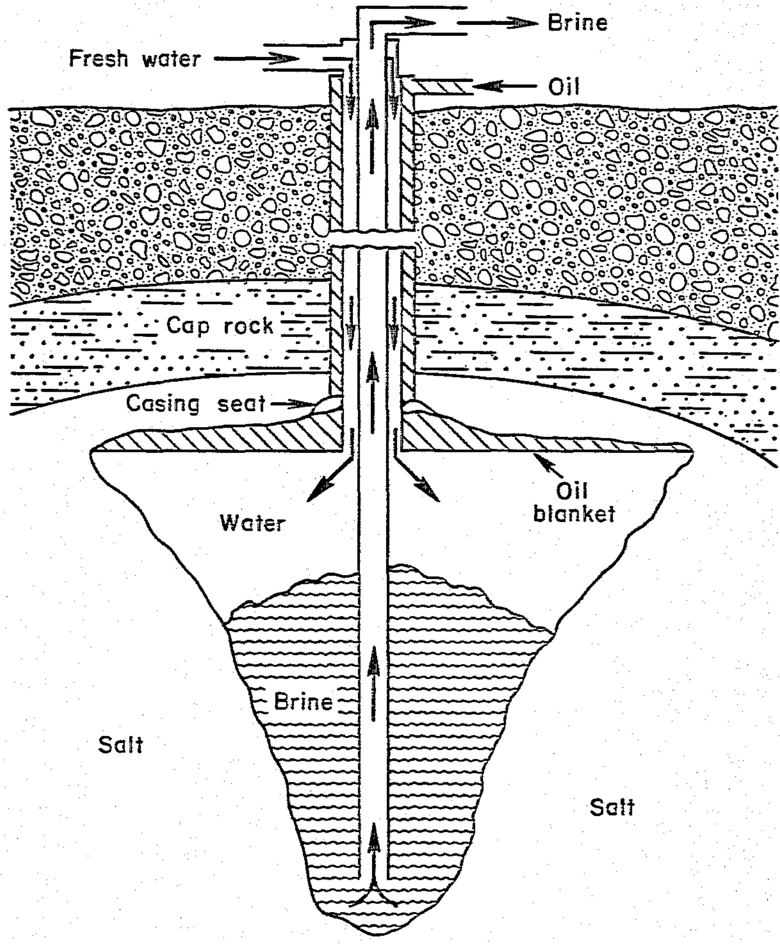

FIGURE 6. - Typical solution mining operation in a salt dome.

drilling operation. The outer casing is cemented full-depth from surface to caprock. The inner casing, penetrating a considerable distance into the salt, is also cemented full-depth and is tightly bonded to the salt with expanding cement. A blanket of lighter-than-water, inert fluid, usually oil, is maintained at the top of the cavity. The layer preserves the predetermined minimum allowable roof thickness of the cavity by preventing upward dissolution. If a saturated brine is desired, which is almost always the case, the water is injected at the top of the cavity, allowing dissolution to progress downward through the salt (direct circulation). The depth to which the inner, production tubing is set determines the elevation of the cavity floor and, from a practical standpoint, the life of the cavity.

The production rate of saturated brine is limited by the overall dissolution rate of the salt. The flow rate of injected water, which directly controls the rate of outflowing brine, is adjusted within the range of values at which the emerging brine will be saturated. A typical solution mined cavern inside a salt dome may be hundreds of feet in height and have a maximum diameter of 500 to 600 feet. A total cavity volume of 25 million ft^3 is not unusual. The limitations on the ultimate maximum diameter of a cavity are imposed by its proximity to possible additional cavities or by structural limitations of the roof.

Preserving the structural integrity of the salt plug and maintaining conditions of isolation for the cavity are the objectives of solution mining in salt domes. This is accomplished by:

- Creation and maintenance of tight seals between cemented casing and salt.
- Operation at down-hole pressures considerably below the lithostatic pressure.
- Maintenance of safe distances between the cavity surface and outer surface of the salt plug and between the cavity surface and possible additional cavities.

A continuous and accurate record of total cavity volume is important, and is accomplished by metering the flows of injected water and produced brine. Sonar measurements of cavity geometry are made periodically to delineate the cavity shape.

In thin bedded salt strata, solution mining is conducted by a method involving the use of at least two wells. The technique is shown schematically in figure 7. After two wells have been drilled into the salt layer, communication between them is established by hydraulic fracturing.

A hazard affecting operations in salt domes and strata is the destruction of the lower portions of the production tubing by large chunks of salt, anhydrite, or rock, which may become dislodged during the dissolution progress.

Solution mining of potash is practiced at Moab, Utah, by Texasgulf (11) and consists of solution mining, solar evaporation and beneficiation. This is the only solution mine to use solar evaporation. The process consists of filling mined-out workings with fresh water, removing the saturated brine

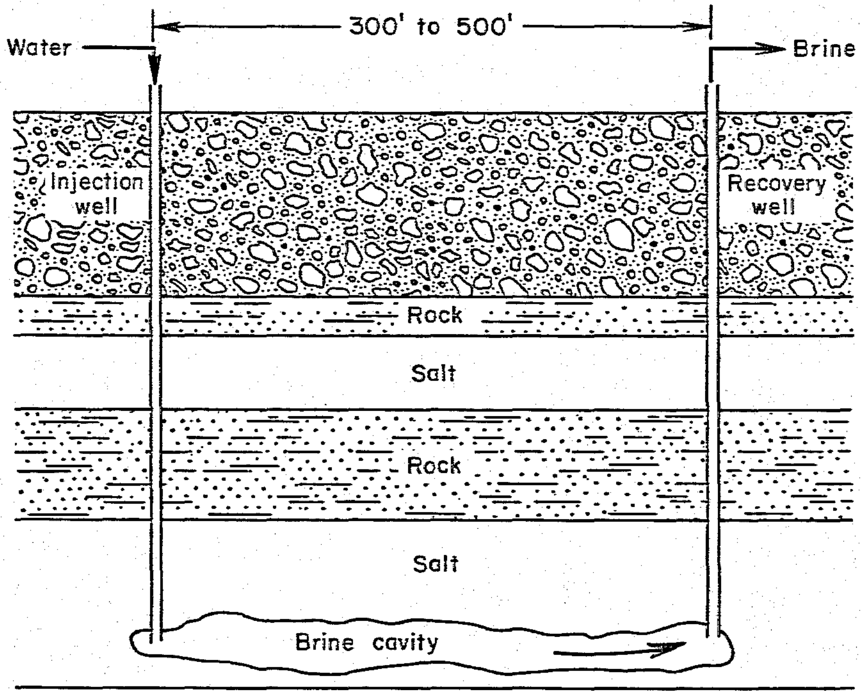

FIGURE 7. - Typical multi-well solution mining operation in bedded salt.

from the mine at the time fresh water is injected, pumping the brine to solar evaporation ponds, harvesting the precipitated salts, slurrying the recycled saturated brine, and pumping the resultant slurry to the plant for processing through a flotation circuit, where potassium chloride is recovered and marketed as fertilizer. About 340 miles of mine workings are used in the leaching operation and permit up to 3,600 gpm of water to be pumped underground through 12 well holes. The deposit is more than 2,700 ft below the surface. As the water flows through the mine, the brine becomes saturated with potassium chloride and sodium chloride and picks up minor quantities of calcium chloride and insoluble clay slimes. The saturated brine is withdrawn from one large extraction hole at 33° C which is the natural heat in the mine. Solution is pumped about 7 to 12 months per year to meet the requirements of the evaporation ponds. The retention time in the mine is 300 to 350 days. The water input rate to the mine is controlled by the need for brine in the evaporation pond area.

Water is removed from the brine by solar evaporation. A mixture of KCl and NaCl solids are deposited in approximately 400 acres of ponds. Production of the solar evaporation operation is a function of the evaporation area available, evaporation rate, and brine concentration. Radiation-absorbing dyes are used as brine additives to increase the evaporation rate. The 23 ponds vary in size from 6 to 52 acres and have been lined with PVC to prevent brine leakage. To protect the lining from equipment when harvesting the deposit of salt, a 6-inch salt base is maintained. The ponds are only 30-inches deep, and markers are used to measure the solids and brine depth during evaporation. After the water has been removed from the ponds, the deposit is harvested with scraper-loaders which are equipped with lasers to control the depth of cuts. The harvest is transported to a crusher station located at the pond site. The crushed material is slurried with brine and pumped to the plant site located approximately 3.5 miles away.

The slurry from the ponds is processed by standard potash beneficiation techniques. An amine-oil type collector system is used to float the potassium chloride from the waste salt. After a final water leach to remove the small amount of sodium chloride in the flotation concentrate, the >60-pct K_2O product is dried and stored. The different grades of potash produced include coarse, soluble, standard and granular. Granular potash is made in a separate circuit, which uses a compaction method.

A large test mine for extracting trona by solution mining at Green River, Wyo., was announced by FMC in 1981 (10). The mining technique will be similar to that used for bedded salt deposits and will consist of an injection well and a recovery well separated by 2,000 feet. The two wells will be connected by hydro-fracturing. Solution from a nearby trona processing plant will be injected. The recovered solution will be sent to the plant for soda ash production. The mine will produce approximately 20 pct of the output of the planned full-scale operation.

SUMMARY

In-place leaching is a recovery procedure which is attractive for small or uneconomic-to-mine deposits in the uranium industry and for copper deposits having the proper geomorphology for leaching. The combination of easily solubilized minerals, relatively shallow and permeable deposits, and efficient metal recovery techniques make in-place leaching of uranium and copper technically attractive. Competitive capital cost, little environmental degradation and fast return on investment provided the economic incentives that have led to a number of pilot and commercial scale in-place leaching projects in the United States. In addition, injection of natural and augmented mine waters into the low-grade peripheral rock surrounding mined out sections of underground mines will continue to supply significant quantities of uranium and copper at existing mining-milling complexes.

Solution mining of evaporite deposits is the largest application of in-place leaching. More than 24 million tons of NaCl and smaller amounts of KCl are produced annually.

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