CHAPTER 11.3

Heap Leaching

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HISTORY

The method of heap leaching has a long history in the mining business. In the mid-1500s, mines in Hungary recycled solutions bearing copper through waste rock for additional copper recovery. Around that same time, Georgius Agricola wrote about piling rocks in heaps and sprinkling them with water for alum recovery in his book *De Re Metallica* (Agricola 1556). At the original Rio Tinto mine in Spain, acid solutions were added to large heaps of copper oxide ores circa 1750. In the 1950s, heap leaching was used for uranium extraction from ore. It was not until 1967 that heap leaching was developed for precious metals by the U.S. Bureau of Mines; the first large-scale gold heap leach project was at Cortez, Nevada. Fewer than 20 years after heap leaching of gold was first developed, it accounted for 30% of all gold production in the United States. In parallel with gold heap leaching, the last 40 years have seen a tremendous expansion of copper dump and heap leaching (Scheffel 2002). Uranium ores have been heap leached with both acid and alkaline solutions since the 1950s. A list of current and historical uranium heap leach operations can be found on the Web site for the World Information Service on Energy: Uranium Project (WISE 2007). Heap leaching of nickel laterites is still in its infancy with only one project near production, the Çaldag project in Turkey.

HEAP LEACHING EXPLAINED

In a simplistic sense, heap leaching involves stacking of metal-bearing ore into a "heap" on an impermeable pad, irrigating the ore for an extended period of time (weeks, months, or years) with a chemical solution to dissolve the sought-after metals, and collecting the leachant ("pregnant solution") as it percolates out from the base of the heap. Figure 11.3-1 is an aerial photograph showing the typical elements of a heap leach operation: an open-pit mine is shown on the left; on the right is a 2-Mt heap of crushed, conveyor-stacked ore on a plastic pad. Pregnant and barren solution storage ponds are located downslope from the heap. Buildings include a solution process facility for recovering metals from the pregnant solution, a laboratory, a maintenance shop, and administration offices. For a small operation such as the one illustrated here, very limited infrastructure is required.

In a more complex sense, heap leaching should be considered as a form of milling. It requires a nontrivial expenditure of capital, and a selection of operating methods that trade cost against marginal recovery. Success is measured by the degree to which target levels and rates of recovery are achieved. This distinguishes heap leaching from dump leaching. In dump leaching, ores are stacked and leached in the most economical way possible, and success is measured by any level of net positive cash flow.

WHY HEAP LEACHING?

Options for recovering metals from ore are many, including agitation leaching, gravity separation, magnetic separation, flotation, and vat leaching. If the ore can be heap leached (which requires good metals recovery by leaching and a rock type that allows the construction of permeable heaps), this technique offers some significant economic benefits. Recent large-scale, very simple heap leaches (40,000+ t/d) have been constructed for a total project capital cost as low as $3,000 per daily metric ton of ore processed, whereas the total capital costs for an agitation leaching plant are often $15,000–$35,000 per daily metric ton. The capital costs of a flotation plant are $10,000–$25,000 per daily metric ton. Another advantage of heap leaching is that it is a chemical process and the product of the leach operation is usually a metal. For gold and silver ores, the primary product at the mine for a leaching operation is an impure gold/silver (doré) bar that can be sold for 95% or more of the quoted price for the metals recovered from the ore. For copper ores, the primary product is usually copper metal that can also be sold for a high percentage of its value. In comparison, flotation plants, which are the primary competitor to the chemical leaching processes, produce a concentrate of the main value mineral(s), which often carries lower-value components and must be sold to a smelter so that the realizable value of gold, silver, and copper is often only 60% of the quoted metal price of the recovered metals.

A number of factors will determine whether heap leaching is the best fit for a project:

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Source: Kappes 2002.

Figure 11.3-1 Heap leach installation at Mineral Ridge, Nevada

- **Risk.** An increasing number of mining projects are being developed in exceedingly remote locations or places with political and social upheaval. It can be a wise choice to select heap leaching in these situations where a mill, with higher capital costs and more complex equipment systems, would be harder to maintain (or stop and restart) as social and political changes occur.
- **Lack of sufficient reserves.** In many underground and some open-pit mining situations, it is difficult (occasionally even impossible) to develop a large ore resource early in the project. Heap leaching offers a very quick, low-cost avenue for treating such ores. As an example, the Sterling mine in Beatty, Nevada (Imperial Metals Corporation) began life as an underground mine with a reserve of 100,000 t (metric tons) of ore at a grade of 11 g Au/t but eventually heap leached nearly 1 Mt.
- **Differential recovery is not sufficient to justify the added investment.** The operating cost plus debt service for a medium-sized mill (3,000 t/d) will typically be $34/t of ore treated, whereas the comparable cost for the heap is $12/t (year 2009 cost basis). Since the heap leach typically gets 25% less recovery than the mill, the gross value of the ore would typically have to be greater than $85/t in order to justify the mill.
- **Capital is very difficult or expensive to raise.** Heap leaching can give a small company a project that can catapult it into the "big league" from a relatively small investment. Often early-stage capital can be raised only by excessive equity dilution or acceptance of onerous bank covenants. The heap leach also gives the management of a small company more time to build up an experienced operational staff before it tackles more complex processes.

HEAP LEACHING CONFIGURATIONS

Configurations of heap leaching available include dynamic heaps, permanent single-lift and multilift heaps, and valley-fill heaps.

Dynamic Heaps

Dynamic heaps reuse the same lined area by loading the ore onto the pad, leaching, washing, and then removing the ore from the pads. They are also referred to as "on/off heaps." The advantage of an on-off heap is that a large amount of ore can be leached in a limited area in relatively thin layers. For ores where the permeability of thicker layers cannot be maintained, which is typical of oxidized copper ores, dynamic heaps often offer the only option. One factor often overlooked is that the leached ore is still an environmental liability and must be moved to another lined area. However, the water balance is easily manageable because of the limited area of the pads. The small area also makes it possible to cover the heap if necessary. Dynamic heaps are applicable to low-grade, precious metal ores containing sulfides that will start to oxidize to form acid within 1 to 3 years. The benefit of using a dynamic heap for this type of material is that the values can be recovered during the short leach time associated with the dynamic heap and the generation of acid would occur in the waste dump, not affecting the leach process.

The pad below a dynamic heap needs to be of sturdier construction than that for a permanent heap because there is more traffic at elevations close to the pad. Pads for dynamic heaps are frequently made of concrete or asphalt for this reason, though with careful ore removal a geomembrane (plastic liner) could be used. Slowly leaching ore can be re-treated by simply restacking it along with the new ore, but this will reduce capacity. Typically the maximum recovery is not reached with dynamic heaps because of the limited time frame for leaching. Before the ore can be removed from the pad, it is usually washed to recover any dissolved values and detoxified if necessary.

Permanent Heaps

In permanent heaps, the ore is stacked on a low-permeability surface and never removed. While this definition also applies to valley-fill heaps, the term *permanent heap* is usually reserved for a heap that is stacked on a relatively tabular ground surface where solution can exit at multiple points across the face of the heap. To expand the available volume for stacking ore, the pad is either expanded or additional lifts are added on top of the ore already stacked. The primary advantages of permanent heaps are that operations are less expensive than dynamic heap operations, and they allow for much longer leach times (up to several years).

Multilift heaps have been built as high as 200 m with successive lifts stacked on top of previously leached lifts. Single-lift heaps are appropriate for some ore types or leaching situations where, for example, the ore is high grade and not very permeable. For single- or multilift permanent heaps, the initial capital cost is relatively low because the liner does not need to be as robust as for a dynamic heap, and a small area can be lined at first with expansion in subsequent years. As multilift heaps grow taller, there are added operating costs for pumping solutions and transporting ore to higher elevations. Permanent heaps require a large area with gently changing topography. The large area required often leads to issues with the water balance in high-rainfall environments, but permanent heaps can be effectively used where rainfall exceeds 2.5 m/yr.

Valley-Fill Heaps

A valley-fill heap leach is just as it sounds: the ore is dumped at the bottom of a valley and is built up, "filling" the valley. Valley-fill heaps are built in areas that do not have enough level terrain to build an expanding permanent heap. Valley-fill heaps can accommodate long leach times well. A valley-fill expands upward and outward as the valley widens near the top. The necessity for multilifts means that the ore should be strong and maintain high permeability under high loads. The pregnant solution is often stored inside the bottom of the heap and a small pond is used to collect the solution for recovery. This has advantages of less cost in liner, less precipitation collection, and it can keep the solution from freezing in cold climates. If solution is stored within the heap, a better liner needs to be in place because of hydraulic head on the liner. The front slope of the heap needs to be thoroughly designed and very stable to prevent any catastrophic failure. Frequently a retaining structure, or dam, is used to support the toe of the heap.

GEOLOGY OF GOLD DEPOSITS

Carlin-Type Sedimentary Ores

These ores consist of shales and "dirty" limestones containing very fine (submicroscopic) gold. Oxidized ores leach very well, with low reagent consumption and production recovery of 80% or better being achieved. Ores are typically coarse-crushed (75 mm) but may show recovery of 70% or better at run-of-mine (ROM) sizes. The largest of northern Nevada's heap leaches (Carlin, Goldstrike, and Twin Creeks) treat this type of ore. Unoxidized ore contains gold locked in sulfides (typically 1%–3% pyrite) and also contains organic (carbonaceous) components, which absorb the gold from solution. This ore shows heap leach recovery of only 10%–15% and is not suitable for heap leaching. Because of the different ore types, the northern Nevada operations (for instance, Barrick's Goldstrike mine) may employ roasters, autoclaves, agitated leach plants, and heap leaches at the same mine site. Crushing is usually done in conventional systems (jaw and cone crushers) and ores are stacked by trucks.

Low-Sulfide Acid Volcanics or Intrusives

Typical operations treating this type of ore are Round Mountain (Nevada) and Wharf mine (South Dakota, United States). Original sulfide content is typically 2%–3% pyrite, and the gold is often enclosed in pyrite. Oxidized ores yield 65%–85% recovery but may have to be crushed to below 12 mm. Usually the trade-off between crush size and percent recovery is a significant factor in process design. Unoxidized ores yield 45%–55% gold recovery and nearly always need crushing. At Round Mountain, approximately 150,000 t/d of low-grade oxide ore is treated in truck-stacked ROM heaps, 30,000 t/d of high-grade oxide ore is treated in crushed (12 mm) conveyor-stacked heaps, and 12,000 t/d of unoxidized ore is treated in a processing plant (gravity separation followed by leaching in stirred tanks). Primary and secondary crushing is done using jaw and cone crushers; finely crushed ore contains enough fines that conveyor stacking is preferred over truck stacking.

Oxidized Massive Sulfides

The oxide zone of massive sulfide ore deposits may contain gold and silver in iron oxides. Typically, these are very soft and permeable, so crushing below 75 mm often does not increase heap leach recovery. The Filon Sur ore body at Tharsis, Spain (Lion Mining Company) and the Hassai mine in Sudan (Ariab Mining Company) are examples of successful heap leaches with this type of ore. Because the ore is fine and soft, the ore is agglomerated using cement (Hassai uses 8 kg cement/t), and stacking of the heaps is done using conveyor transport systems.

Saprolites/Laterites

Volcanic- and intrusive-hosted ore bodies in tropical climates typically have undergone intense weathering. The surface cap is usually a thin layer of laterite (hard iron oxide nodules). For several meters below the laterite, the ore is converted to saprolite, a very soft water-saturated clay, sometimes containing gold in quartz veinlets. Silver is usually absent. These ores show the highest and most predictable recovery of all ore types, typically 92%–95% gold recovery in laboratory tests, 85% or greater in field production heaps. Ores are processed at ROM size (which is often 50% minus 2 mm or 10 mesh) or with light crushing. Ores must be agglomerated and may require up to 40 kg of cement/t to make stable, permeable agglomerates. Many of the western African and central American heap leaches process this type of ore; good examples are Ity in the Ivory Coast and Yatela in Mali. When crushing is required, one or two stages of toothed roll crushers (Stamler-type feeder-breaker or a mineral sizer) are usually employed. Conveyor systems are almost always justified; ore can be stacked with trucks if operations are controlled very carefully.

Clay-Rich Deposits

In some Carlin-type deposits and volcanic-hosted deposits, clay deposition or alteration occurs along with gold deposition. These ores are processed using the same techniques as for saprolites, except that crushing is often necessary. Because of the mixture of soft, wet clay and hard rock, a typical crushing circuit design for this type of ore is a single-stage impact crusher. Truck stacking almost always results in some loss of recovery. Agglomeration with cement may not be necessary, but conveyor stacking is usually employed.

Barneys Canyon (Utah, United States) uses belt agglomeration (mixing and consolidation of fines as it drops from conveyor belts) followed by conveyor stacking. The La Quinua operation at Yanachocha, Peru, employs belt agglomeration followed by truck stacking.

Silver-Rich Deposits

Nevada deposits contain varying amounts of silver, and the resulting bullion may assay anywhere from 95% gold and 5% silver to 99% silver and 1% gold. Mexico also has multiple silver-rich deposits, like the Dolores and Ocampo projects. Silver leaches and behaves chemically in the same way as gold, although usually the percentage of silver recovery is significantly less than that of gold. Examples of nearly pure silver heap leaches are Coeur Rochester and Candelaria mines in Nevada, and Comco in Bolivia.

GEOLOGY OF COPPER DEPOSITS

Copper occurs in three basic assemblages: oxides, secondary sulfides, and primary sulfides. Porphyry deposits produce the bulk of the world's copper, and if these outcrop, they usually contain all three mineral assemblages (Bartlett 1998). The secondary sulfides are often the highest grade because of the oxidized cap leaching naturally and depositing copper in the secondary sulfide zone. If acidic conditions are not sufficient, the copper is not transported and an oxide deposit is formed.

Normally, there is no distinct zoning and there is frequently a transition zone from oxides to sulfides. The varying chemistry of copper makes the chemistry of copper heap leaching more difficult and complex than that of gold or silver. Adding to the chemical issues, feldspar minerals in copper ores often break down over several weeks of leaching to form clays, which reduce the permeability of the heap. Dump leaches—where uncrushed low-grade mine waste is leached with dilute acid—are fairly common at copper mines because extra copper can be recovered at a very low cost.

Oxide Copper Ores

There is a wide range of copper oxide minerals. With the range of minerals comes a range of metallurgical responses. Most copper oxide minerals leach relatively quickly although some, especially the silicates (like chrysocolla), may be only partially soluble because of the formation of impermeable coatings.

Sulfide Copper Ores

There are primary sulfides, like enargite and chalcopyrite, and secondary sulfides, like chalcocite, bornite and covellite. The secondary sulfides usually leach faster and more completely than the primary sulfides. All sulfides need an oxidant present for dissolution, and the slow introduction of oxygen or oxidizing chemicals can result in a significant lengthening of leach times over what was predicted by laboratory tests. Within the heap, oxygen is usually converted by bacteria into oxidized (ferric) iron, and it is this ferric iron that reacts to oxidize the sulfides, so the heaps must be built in such a way as to encourage the growth of bacteria.

GEOLOGY OF URANIUM DEPOSITS

Sedimentary Uranium Deposits

Oxidized uranium is readily soluble and may be transported from granites or tuffs by groundwater to another location where it is concentrated. The uranium may precipitate in an area for a number of reasons, including lower temperatures and pressures, reduction, ion exchange, neutralization, and chemical replacement. Generally, for ore bodies, the uranium is deposited by reduction from the soluble, hexavalent uranium dioxide to an insoluble tetravalent state. The classic uranium deposits of the western United States are "roll front" deposits in which uranium is dispersed from sandstone and reprecipitated in a continually moving zone.

Granitic Uranium Deposits

Uranium may also be concentrated as large bodies of granite solidify. The initially low concentrations of uranium are continually forced into the remaining solution in the granite until small concentrated amounts of uranium-bearing solutions are left. The fluid can get into fissures in the surrounding rock and form veins of ore.

GEOLOGY OF NICKEL DEPOSITS

Nickel laterite deposits are created when a parent rock is weathered by high rainfall and elevated temperature, typically in a tropical or subtropical climate. The minerals that dissolve easily are removed by the rainfall, leaving behind higher concentrations of the less-soluble elements like iron and aluminum. Nickel is somewhat mobile and concentrates near the base of the leached zone.

CHEMISTRY OF GOLD DEPOSITS

The chemistry of leaching gold and silver from their ores is essentially the same for both metals. A dilute alkaline solution of sodium cyanide (NaCN) dissolves these metals without dissolving many other ore components (copper, zinc, mercury, and iron are the most common soluble impurities). Solution is maintained at an alkaline pH of 9.5–11. Below a pH of 9.5, cyanide consumption is high. Above a pH of 11, metal recovery decreases. A pH above 11 can also result in dissolving silica, which can cause problems with scale control and blinding of carbon.

Many heap-leachable ores contain both gold and silver. Deposits in western Africa and Australia tend to be very low in silver, while those in Nevada and Mexico are highly variable, ranging from pure gold to pure silver. Silver is usually not as reactive with cyanide as gold. This is because gold almost always occurs as metal, whereas silver may be present in the ore in many different chemical forms, some of which are not cyanide soluble. The consequence is that heap recoveries for gold typically range from 50% to 90% while silver typically ranges from 25% to 60%.

Recovery of gold from leach solutions is usually accomplished by adsorption of the gold cyanide complex onto granular activated carbon by pumping the solution through columns filled with the carbon. The leach solutions are recycled to the heap. Gold-rich solution from the heap usually contains only a few parts per million gold, whereas the carbon loads up to about 5,000 ppm. Gold is removed from the carbon by contacting it with a hot chemical solution that is then sent to an electrolytic cell for production of gold metal. This is usually melted on-site to produce a doré bar for sale to refineries (Marsden and House 2006).

The recovery of silver, and the recovery of both gold and silver from solutions high in silver, is usually accomplished using the Merrill–Crowe process. In this process the metal-rich solution from the heap is prepared by filtration and then vacuum treated to remove oxygen from solution. Zinc dust is added to precipitate the metals, and the precipitate is collected on filters. This precipitate is melted on-site to produce a gold/silver doré bar.

The level of cyanide in the heap leach on-flow solution typically ranges from 100 to 600 ppm NaCN, although some ores may require more than 1,000 ppm. Cyanide consumption via complexation, volatilization, natural oxidation, or oxidation by ore components typically ranges from 0.1 to 1.0 kg/t of ore. Cement and/or lime consumption ranges from 0.5 to 70 kg/t of ore. Several operations use cement for alkalinity control (instead of or in addition to lime) as well as for agglomeration.

Other leaching agents—thiosulfate, thiourea, hypochlorite, bromine—have been experimented with as an alternative to cyanide, but cyanide is by far the most effective and the most environmentally friendly leaching agent.

CHEMISTRY OF COPPER DEPOSITS

Copper ores are nearly always leached with a dilute sulfuric acid solution. Copper in heap pregnant solution is typically several grams per liter, whereas for gold/silver ores the solutions contain only a few parts per million of metals. With copper oxides it is not uncommon for the solution availability to the metals in the ore to limit the leach rate of copper. If a slow leaching rate is simply due to the avpplication rate, this can be remedied, but it is often due to the capillary action in the ore particles, and this is difficult to speed up. Wetting agents have been used to overcome this, with limited success.

Depending on the ore, the natural production of sulfuric acid can be sufficient for the leaching process. The pH of the leach solution needs to be in the range of 2.0 to 2.8 or lower to prevent hydrolysis of the ferric ions. If other oxidizing sulfides (such as pyrite) are present, the acidity can drop to the point where gangue minerals react quickly to form clays, which plug the heap.

Recovery of copper from leach solutions is usually accomplished by processing the copper-rich solution through a solvent extraction plant where copper is extracted into an organic liquid and then back-extracted into concentrated acid for concentration and purification of the copper solution. The barren solution is recycled to the heap. The concentrated solution is sent to electrolytic cells for production of metallic copper. Copper cathodes produced from this process are normally of marketable purity and are sold directly to copper end users (Jergensen 1999).

CHEMISTRY OF URANIUM DEPOSITS

Uranium ores are typically leached with dilute sulfuric acid, often naturally generated, or ammonium carbonate. The tetravalent uranium in oxide minerals needs to be oxidized to the hexavalent state. This is normally done in an acid heap by natural bacterial oxidation, but use of chemical oxidants may be employed. For an alkaline heap, hydrogen peroxide, H_2O_2, is usually employed as an oxidant. The roll of the ferric ion in the oxidation in an acid uranium heap is the same as that in copper heaps. As a result of similar chemical processes, acidic uranium and copper heaps have the same issues to overcome (Merritt 1971).

If lime is present in the host rock, this can cause permeability issues as the leach solution dissolves and reprecipitates the calcium as gypsum. It is common to begin the leach process at a low sulfuric acid concentration and increase it after the gypsum has had a chance to reprecipitate throughout the heap instead of in a single layer, as would occur if higher initial acid concentrations were used. If the lime in the host rock causes excessive acid consumption, alkaline ammonium carbonate $[(NH_4)_2CO_3]$ leaching can be used.

Ammonium carbonate leaching is selective to uranium and as a result the uranium bearing minerals need to be exposed to wetting, possibly requiring finer crushing.

Recovery of uranium from both acid and alkaline leaching is typically accomplished by upgrading solutions with solvent extraction or ion exchange resins followed by a caustic treatment to precipitate "yellow cake" uranium, which can be refined to uranium dioxide (UO_2).

CHEMISTRY OF NICKEL DEPOSITS

Heap leaching of nickel has been proposed but rarely applied. Either hydrochloric (HCl) or sulfuric (H_2SO_4) acid may be used as lixiviants. Recovery of nickel from recycled heap solution requires expensive neutralization of the acid, and this is a barrier to application of the process.

LABORATORY WORK

As with any processing method, it is very important to base the design on the results of a comprehensive program of laboratory testing. For a proper heap leach laboratory program to be developed, it helps to know early on, preferably in the exploration stage, that heap leaching may be an option. To conduct representative column tests, the samples need to be coarse rocks that cannot be produced from reverse circulation drilling. Either large-diameter core diamond drilling (100–200 mm) or bulk sampling (tons) is required. It is common practice to drive a drift into the ore body to take a sample, but as the resource gets larger, this sample becomes less representative. The initial ore samples are seldom representative of the entire ore body; therefore, laboratory tests, including column leach tests, should be continued on a regular basis during mining.

After heap leaching is selected, there is a range of variables that need to be tested. These include crush size, heap stability, permeability versus heap height, solution application rate, reagent strength and consumption, the need for agglomeration, and the type (usually portland cement for gold/silver heaps) and the amount of agglomerating agent required, leach time, and percent recovery.

Heap leaching has inherent risks that can be largely eliminated if the design and operating practices follow the results of the initial and ongoing laboratory testing. The risks result from the nature of the operation. The results of the process are usually not known for several weeks or even months after the ore is stacked, and at this point it is not economical to reprocess the ore. Mistakes made in the initial plant design or incorrect operating practices (e.g., not crushing finely enough or not agglomerating or stacking properly) can result in cash-flow issues that might persist for up to a year after the problem is solved.

An on-site laboratory is an important part of the infrastructure at a heap leach operation. It should include an analytical section (for ore control) and a metallurgical testing section that regularly runs column leach tests on production samples. In addition to the standard production column leach tests, periodic test programs should be run to check the effects of chemistry, crush size, and agglomeration. For a small operation processing fewer than 5,000 t/d of ore, staffing should involve two or three technicians for sample preparation and assaying, and one metallurgist to conduct process tests. Large operations may have a laboratory staff of 10 to 15 people and around-the-clock operation.

HEAP PERMEABILITY AND FLOW EFFICIENCY

The key element in a successful heap leach project is a heap with high and uniform permeability. In any heap there are three zones of different flow regimes:

1. Coarse channels, which allow direct short-circuiting of solution from top to bottom
2. Highly permeable zones, in which solution is efficient at contacting the rock and washing the values downward in "plug flow"
3. Zones of low permeability where high-grade solution or unleached ore may be trapped

Efficiency of Solution Displacement

If the heap was "ideal" (i.e., moving in true plug flow), then when one displacement volume of solution was placed on top of the heap, it would fully replace the solution in the heap. This would be 100% wash efficiency. In practice, the "best" heap leaches exhibit a wash efficiency of about 70%. At 70% per displacement, three displacement washes are required to achieve a recovery of 95% of the dissolved metals. A fourth "displacement" is required, initially, to saturate the ore. Since a typical heap contains 20% moisture, 95% recovery (of the dissolved value content) requires that 0.8 t of solution must be applied to each ton of ore. In gold heaps, typical practice is to apply 1.3 t of solution per ton of ore during a 70-day primary leach cycle. This suggests two things: (1) most heap leach operations are able to maintain reasonably good permeability characteristics, yielding at least 50% wash efficiency; and (2) a high percentage of the recoverables is solubilized early in the 70-day leach cycle.

Drainage Base

A drainage base of crushed rock and embedded perforated pipes should be installed above the plastic leach pad and below the ore heap. The importance of this drainage base cannot be overemphasized. Solution should percolate vertically downward through the entire heap and then enter a solution removal system with zero hydraulic head. If the drainage base cannot take the entire flow, solution builds up in a stagnant zone within the heap and leaching within this stagnant zone can be very slow.

To put this in context, a "typical" heap might run 500 m upslope from the solution collection point. All of the on-flow solution in a 1 × 500-m strip must flow out at the downslope edge of the heap through the drainage base, which is typically 0.65 m thick. The design of the horizontal percolation rate through the drainage base is therefore nearly 800 times the design rate of the heap itself. This is not a difficult engineering accomplishment since flow is carried in pipes within the base.

At one Australian copper heap leach operation, three adjacent leach panels were built. The two flanking panels had a good installed drainage base, but the center panel did not. Recovery in the center panel was depressed 20% by the poor drainage base. A similar effect has been seen but not quantified at some gold heap leach operations.

Recovery Delay in Multilift Heaps

As subsequent lifts are stacked, the lower lifts are compressed and the percentage of low permeability zones increases. The first solution exiting an upper lift may have a values concentration of up to three times that of the ore. If impermeable zones have developed in a lower lift, high-grade solution may be trapped, causing a severe reduction in recovery rate and possibly in overall recovery percentage. The highest heap leaches currently in operation are 200 m high, with about 10 lifts of ore. Hard ore, crushed or ROM, can withstand the resulting pressure without significant permeability loss. Many softer ores can be agglomerated with enough cement so that they can perform under a load of 30 m; some agglomerated ores perform satisfactorily to 100 m. These properties can be properly evaluated in advance in laboratory column tests, which are run under design loads.

The delay in recovery as lifts are added to the heap is partly a function of the impermeability of the lower lifts and partly a function of the wash efficiency discussed earlier. The net effect is that average recovery is delayed as the heaps get higher and overall pregnant solution grade decreases (requiring more solution processing capacity).

Intermediate Liners

If the permeability of lower lifts becomes a serious problem, it is possible to install intermediate liners, though this is not recommended. Two problems occur with installing an intermediate liner: (1) the heap below the liner is compressed as the upper lift is placed, resulting in differential settlement and possible tearing of the liner; and (2) the ore below the liner cannot be washed with water, which is sometimes required as part of final heap closure.

SOLUTION APPLICATION RATE AND LEACH TIME

With regard to sprinkling rate, the timing for metals recovery is a function of the following factors:

- The rate at which the metal dissolves. Coarse particles dissolve very slowly, and may not fully dissolve for several months in a heap leach environment.
- The percentage of the ore minerals that exist as free or exposed particles
- The rate of diffusion of the solution into rock fractures, and dissolved metal back out of the rock fractures. Where ore minerals occur on tight fractures or in unfractured rock, the rock must be crushed into fine particles to achieve target rates and levels of recovery.
- The effect of chemical reactions within the heap, or within rock particles, which consume the reagents needed for leaching
- The rate of washing the values off the rock surfaces and out of the lift of ore under leach. This is a complex issue that depends on the overall permeability of the lift and the local permeability variations due to segregation and compaction as the lift is being constructed.

These factors cause wide theoretical differences in the response of various ores to leaching. However, in practice, most heap leach operations apply solution to crushed-ore heaps within a fairly narrow range of flows. The typical range is from 8 to 12 $L/h/m^2$, though some heaps range far above or below these rates (Van Zyl et al. 1988). Some operations start at higher solution application rates to saturate the ore and decrease the application rate with time. Other operations will start solution application very slowly until the heap is thoroughly wetted, to prevent the formation of preferential channels of water flow and then increase the application rate.

Laboratory columns always respond much faster than field heaps. Generally the cause of this problem is reduced reagent-to-values contact in a production heap. Two major reasons for the reduced contact are: (1) the ore is placed in the laboratory column much more uniformly so that percolation is more effective; and (2) the solution-to-ore ratio (tons of solution per ton of ore in a given time frame) is generally higher in laboratory columns than in field heaps. Both small- (150-mm) and large-diameter (1,000-mm) column tests tend to leach similarly. For some field heaps, notably where the ore is fine crushed and the ore leaches quickly, the solution/ore ratio is a more important factor than overall leach time. However, for the majority of heap leaches, time seems as important as specific application rate. The general target for the solution/ore ratio is between 1:1 and 1.5:1.

For ores with very slow leaching characteristics, an intermediate pond and a recycle stream may be added to the circuit, so that each ton of ore sees 2 t of leach solution during an extended leach period. The process plant treats only the final pregnant stream—1 t of solution/t of ore.

The use of multiple cycles is good operating practice for single-lift heaps of high-grade ore. However, for multilift heaps this is not the case. Heap modeling indicates that after the heap attains a height of three lifts, the intermediate solution contains almost as much metal as the pregnant solution. Recycling results in a significant buildup of dissolved values

Figure 11.3-2 Heap leach installation at Brewery Creek. The open-pit mine is shown in the background. In the center of the photograph is an operating heap leach completely covered with snow.

within the heap, causing a slight overall recovery loss and a cash-flow delay. For multilift heaps, it is often possible to justify an increase in the size of the recovery plant so that only fully barren solution returns to the heap.

It is extremely important to design a heap leach system so that the ore can be leached for a very long time. Unlike an agitated leach plant where the ore can be ground to a fine powder and intensively mixed, heap leaching is not a very energy-intensive process. After a heap is built, one of the most significant variables the operator can employ to solve design or production problems is the leach time. Some operations use on-off leach pads to achieve rapid first-stage recovery and then transfer the ore to long-term heaps to complete the process (Kappes 2002).

SOLUTION APPLICATION

The primary goal in the irrigation of a heap is to apply the solution as uniformly as possible. Solution distribution to a heap is done by flood, spray, or drip irrigation. The choice of irrigation can vary greatly depending on specific heap conditions. In recent years, flood irrigation has become a rarity. Spray and drip irrigation are widely used and frequently both are used on the same heap, depending on the season. The following equipment has become standard in heap leaching.

Drip Irrigation

Drip emitters, which issue drops of water from holes every 0.5–1.5 m across the heap surface, are very common. Drip emitters are small in-line devices spaced along a tube that distributes the solution evenly by forcing the water through a complicated path at each emitter, creating an equal pressure loss for the first and last emitter in a line. Drip emitters are easy to maintain and minimize evaporation and cyanide loss. In very cold climates it is possible to bury the emitters to prevent freezing, as shown at Brewery Creek (Alaska, United States) in Figure 11.3-2. In the winter months, the solution flow is piped directly to the process facility on the lower right. The barren leach solution is heated prior to application on the heap and solution pipes are heat traced. The ponds in the foreground are frozen over but, if necessary, excessive flow may be directed into them. Drip emitters can be advantageous for some copper and uranium heaps because they conserve heat that may be required for biological activity. The main drawback to drip emitters is that they do not provide continuous drip coverage. Thus the top 1 m of the heap may not be leached very well until it is covered with the next lift. Other drawbacks are that emitters, due to their small channels, require intensive (and expensive) use of antiscalant, and the use of in-line filters.

Wobbler Sprinklers

Wobbler sprinklers are used at a large number of operations. Their main advantages are that they issue coarse droplets, which control but do not eliminate evaporation, and they deliver a uniform solution distribution pattern that ensures uniform leaching of the heap surface. The coarse droplet size has another advantage in gold heaps. Cyanide is readily oxidized by air and sunlight, and the wobbler-type sprinkler minimizes this loss (but not as well as drip systems). Wobblers are typically placed in a 6 × 6-m pattern across the heap surface. A disadvantage of all sprinklers is that they require continual servicing, and personnel spend extended periods working in a "rainstorm." Occasional skin contact with cyanide solution does not pose a health problem, but an environment that encourages repeated skin/solution contact is not recommended. Sprinkler maintenance personnel, especially on acid copper heap leaches, wear full rain gear to eliminate any exposure problem, but the working environment (especially in cold weather) is not as pleasant as with drip emitters. Because of the impact of the water on the surface of a heap, wobblers, or any sprinkler system, can lead to the breakdown of delicate agglomerates and migration of fines into a heap. In a tropical climate it may be necessary to use sprinklers because of evaporation issues, but they can cause permeability problems. The influence of the sprinklers on the breakdown of agglomerates and migration of fines can be minimized by placing screen material over the heap to dissipate the impact energy of the water droplets.

Reciprocating Sprinklers

Reciprocating sprinklers shoot a stream, typically 5–8 m long, of mixed coarse and fine droplets. They are not considered ideal for heaps but often find application for sprinkling side slopes since they can be mounted on the top edge to cover the entire slope. If emitters and wobblers are used on side slopes, they must be installed on the slope, which is a difficult and sometimes dangerous place for service personnel to operate from.

High-Rate Evaporative Sprinklers

High-rate evaporative sprinklers typically operate at high-pressures with an orifice designed to produce fine droplets and shoot them in a high trajectory. Evaporative blowers using compressed air to atomize and launch the droplets can also be used. The drifting of the fine particles with wind can cause a concern with chemicals entering the surrounding environment. This type of equipment is not normally used at heap leach operations, but it will become more common as more heaps enter the closure mode where rapid evaporation is needed.

Regardless of the systems used for solution application and management, capital and operating costs for solution handling are usually small.

WATER BALANCE

Since many heap leach operations occur in desert areas where water is scarce, and others occur in environmentally sensitive areas where water discharge is not acceptable, the balance between water collection and evaporation is important. Fortunately, by adjusting the method and scheduling of solution application, it is usually possible to meet the local conditions.

The evaporation of water, regardless of its mechanism, requires a heat input of 580 cal/g of water evaporated. A heap leach gets this heat input from three sources: direct solar heating on heap and water surfaces, latent heat in the shroud of air within the "sprinkler envelope," and latent heat in the air that is pulled through the heap by convection.

The average 24-hour incident solar radiation on a flat horizontal surface ranges from 3,000 kcal/m^2/d in the central United States to about 7,600 kcal/m^2/d in the equatorial desert, which could theoretically evaporate 5–12 L of solution/d/m^2. With a typical heap application rate of 10 L/m^2/h, incident solar radiation could account for an evaporation rate of 2%–5% of applied solution when using sprinklers. Evaporation would be somewhat less when using drip irrigation (1%–4%) because some of the solar energy is reradiated from dry areas on top of the heap. This same heat input would result in pond evaporation of 5–13 mm/d.

Overall evaporative losses include the sprinkler losses, convective loss from air flowing through the heap, and losses due to heating/evaporation from ponds and from other areas not sprinkled. These have been determined at several Nevada operations to be up to 20% of the total solution pumped in summer months, but averaging 10% annually. Thus, direct sprinkler loss accounts for about 60% of the total evaporation. Use of drip irrigation can reduce but not eliminate evaporative loss.

In tropical climates, noticeable losses occur even during the rainy season. On several tropical heap leach projects where rainfall is seasonal and up to 2.5 m/yr, the overall annual evaporative loss from all sources, when using wobbler-type sprinklers operated 24 h/d, is about 7% of the solution pumped. A typical heap application rate is 10 L/m^2/h, or 88 m/yr/m^2. Thus, evaporative loss of 7% is equal to 6.2 m/yr/m^2 on the areas actually being sprinkled. If the heap and pond systems are properly designed, the active leaching area can be up to 40% of the total area collecting rainfall; it is therefore possible to operate in water balance when rainfall is 2.5 m/yr. For these operations, very large solution surge ponds are required.

Where rainfall is high and evaporation rate is low, some operations cover the side slopes with plastic to minimize rain collection. Others have tried to cover the entire heap during the rainy season, but this has not worked very well because of the mechanical difficulties in moving the covers.

In western Africa and Central America, it is acceptable practice to treat and discharge excess solution during the rainy season. Typically, excess process solution is routed through a series of ponds where cyanide is destroyed using calcium hypochlorite [$Ca(ClO)_2$] or H_2O_2, followed by adjustment of the pH to near neutral. The INCO SO_2 system, using copper-catalyzed hyposulfite to destroy cyanide, is also employed for this purpose. Cyanide-free solution is further treated in controlled wetlands (swamps) to remove heavy metals prior to discharge.

The worst water balance situation occurs in cool, damp climates such as in high-altitude operations. In such climates, rainfall and snowfall may be significant and evaporation is minimal. Generally such heaps can stay in water balance with an aggressive program of summer sprinkling. Arctic heap leaches have been able to stay in water balance because precipitation is lower than the total water requirement needed to saturate the ore (Kappes 2002).

LEACH PADS

The leach pad below the heap is a significant element of a heap leach design. The ideal location for the heap is a nearly flat (1% slope), featureless ground surface. Usually some earthwork is required to modify contours, but it is not necessary to eliminate all undulations. It is only necessary that all the solution will flow across the surface toward the collection ditches on the base or the sides of the heap. Where the slope exceeds 3%, the front edge of the heap (30–50 m) should be graded flat to provide a buttress to prevent heap failure. In the western United States, where the water table is often far below the surface, the current practice is to construct the leach pad of 1.5-mm thickness high-density polyethylene or very-low-density polyethylene on a 30-cm-thick layer of compacted clay. A leak detection/water seepage system of pipes is installed below the liner.

HEAP HEIGHT

As discussed previously, for multilift heaps, there is a delay in the recovery and grade. This is not only true for multilifts but also for single lifts as the lift gets taller. A lower recovery grade means that either a larger recovery plant needs to be installed or a lower cash flow will have to be tolerated. The delay in cash flow caused by delayed recovery also needs to be taken into account for additional lifts or height. Depending on the permeability of the material and lift height, the delay per lift can range from 3 to 30 days. It is common to see a delay of 7 days per lift. As a single lift gets taller, there is the added concern of particle size distribution. As the ore is stacked, it rolls down the side slope of the heap. This cascading action naturally segregates the fine particles near the top of the lift, and the large particles near the bottom. The taller the lift the more stringent the controls on this problem need to be. On the other hand, the advantage of taller lifts is that there is less high-grade solution flowing through already-leached ore beneath it. The larger the quantity of high-grade solution flowing through leached ore, the more opportunity there is to lose values. For copper heaps there are additional factors that must be considered when choosing lift height. Copper oxide heaps are frequently limited in height to maintain the pH in the range that keeps the copper soluble. Copper sulfide heaps will create acid within the heap that may cause a pH problem, and these can also easily become oxygen deficient. Because of these issues and permeability problems, copper ores may be leached in "thin layer" heaps where the ore is stacked only 3–4 m high and leached for a relatively short period (weeks instead of months).

With harder ore and quality agglomeration, permeability is not always the driving factor in the ultimate heap height. It may be good operating practice to reduce the heap height in order to maintain a high, consistent solution grade, which is important for planning purposes, especially at very large operations.

MINING, ORE PREPARATION, AND STACKING

Mining of ore for heap leaching employs the same techniques and equipment as mining of ore to feed any other process

Figure 11.3-3 Agglomerating drum and conveyor stacking system with 6-m-high heap

method. Where uncrushed (ROM) ore is placed on the leach pad, ore may be blasted very heavily in order to reduce rock size and improve gold recovery. In high-rainfall environments when processing clay-rich material, it is very important to practice a mining routine that minimizes the amount of rainfall absorbed by the ore.

Ore preparation varies widely. ROM ore may be hauled from the mine and dumped directly onto the heap. At the other extreme from ROM leaches, some heap leaches crush the ore and dry grind it to more than 50% passing 150 μm (100 mesh) and agglomerate the fines (AusIMM 1991). At times, the high-grade ore will be ground and subsequently reblended with the coarse low-grade ore going to the heap. This process is called "pulp agglomeration" and is practiced at Ruby Hill in Nevada.

Ores high in clay (such as saprolites) are typically processed by two stages of crushing using toothed roll crushers, then agglomerated in drums and stacked using a conveyor stacking system. Many ores are crushed and then either truck-stacked or conveyor-stacked without agglomeration. For these harder ores, crushing is usually achieved by a jaw crusher, followed by one or two stages of cone crushing.

Agglomeration

The term *agglomeration* means different things to different operators.

The simplest application of agglomeration is practiced where the ore is hard but contains a large percentage of fines. Agglomeration means simply wetting the ore with water so the fines stick to the coarse particles and do not segregate as the heap is built.

A more involved form of agglomeration is practiced where the ore contains amounts of clay or fines that may begin to plug a heap of untreated ore. Belt agglomeration may be employed. In this technique, cement and water are mixed with the ore at a series of conveyor drop points, and the mixture tends to coat the larger rock particles. The primary goal is stabilization by mixing and contact. A typical conveyor stacking system involves 10 or more drop points, so belt agglomeration may occur as a normal part of the process.

Where ores are nearly pure clays, such as the laterite/saprolite ores in tropical climates, drum agglomeration is usually employed. Figure 11.3-3 shows a typical agglomerating drum. The ore is first crushed finely enough (typically 25–75 mm) to form particles that can be a stable nucleus for round pellets. For gold and silver ores, cement and water are then added and the ore is sent through a rolling drum. The fines and the cement form a high-cement shell around the larger particles, and the rolling action of the drum compacts and strengthens the shell. Copper ores cannot use cement because the sulfuric acid will break it down. Concentrated sulfuric acid is used as a binding agent instead, although the binding effect of sulfuric acid is not very good. Where copper ores are very high in clay or in minerals that decompose in the heap to clay, heap leaching may not be very effective. Drum size and throughput are a function of several factors, but typically a 3.7-m-diameter 10-m-long drum can process 750 t/h. A 2.5-m-diameter drum can process 250 t/h. At the Tarkwa mine in Ghana, two 3.7-m drums were installed to process up to 20,000 t/d of ore. For multilift gold heaps, it is often necessary to use a higher cement addition on the lower lifts, and this is usually determined by laboratory tests in which the ore is leached under the full heap load. Maintaining permeability of the lower lifts is extremely critical to the success of a multilift heap (Kappes 2002).

Truck Stacking

Where rock is hard and contains very little clay, it is possible to maintain high permeability even when ore is crushed and dumped with trucks (Figure 11.3-4). Truck dumping causes segregation, of the ore as it cascades down the slope. To control the degree of this segregation, the ore may be partially agglomerated (wetted to cause the fines to stick to the coarse material) prior to placing in the trucks.

Truck dumping can also result in compaction of roadways on top of the heap. Several studies have indicated large trucks noticeably compact ore to a depth of 2 m. To mitigate this problem, most operations rip the ore after stacking but prior to leaching. The number of ripper passes is important; usually

Figure 11.3-4 A truck is dumping an upper lift onto a lift that is actively under leach. The road formed by haul truck traffic on the heap can be seen on the right.

it is four passes in a crisscross pattern. Some operations practice building an elevated truck roadway that is later bulldozed away. However, this requires substantial bulldozer traffic on the heap surface, which can lead to permeability problems.

Stacking the ore with trucks can result in the tie-up of a large tonnage of ore below the truck roadways. This is a bigger problem for small operations than for large ones, because the roadway width is usually the same regardless of the daily production rate. For a heap leach of 5,000 t/d, the roadways on the heap can tie up one month's ore production. A conveyor system that stacks ore from the base of the lift can reduce the unleached inventory to a few days' production. Because of this inventory reduction, at smaller operations where the ore is crushed, it is usually less capital intensive to install a conveyor stacking system. Conversely, for operations of 100,000 t/d or more, truck stacking is more flexible and may be less capital intensive than a conveyor system.

Conveyor Stacking

Two major types of conveyor stacking systems are used on heaps: radial stacking systems and spreader conveyor systems.

Radial conveyor stacking systems commonly include the following equipment:

- One or more long (overland) conveyors that transport the ore from the preparation plant to the heap. Typically these consist of conveyors up to 150 m or longer.
- A series of 8–15 "grasshopper" conveyors to transport the ore across the active heap area. Grasshoppers are inclined conveyors 20–50 m long, with a tail skid and a set of wheels located near the balance point.
- A transverse conveyor to feed the stacker-follower conveyor
- A stacker-follower conveyor, typically a horizontal mobile conveyor that retracts behind the stacker
- A radial stacker 25–50 m long, with a retractable 5–10-m conveyor at its tip called a stinger. Wheels, discharge angle, and stinger position are all motorized and are moved continuously by the operator as the heap is built.

Radial stackers are usually operated from the base of the lift but may be located on top of the lift, dumping over the edge. Figure 11.3-5 shows a heap that is not only stacked with conveyors on top of the heap but is also stacked in a novel manner: a spiral of one continually climbing lift instead of multiple individual lifts. Inclined conveyors can be installed up the sides of the lower lifts, and the stacking system can be used to build multilift heaps. Stackers for this purpose should have very-low-ground-pressure tires and powerful wheel drive motors to cope with soft spots in the heap surface.

Radial stacking systems can be used for heaps processing up to 50,000 t/d of ore, but beyond that, the size of the stacker (and the bearing pressure that is exerted by the wheels) becomes prohibitive. For operations stacking very high tonnages, large stackers can be mounted on caterpillar tracks to reduce ground pressure.

Spreader conveyors can be used on very-high-tonnage heaps. On on-off (dynamic) heaps, spreader conveyors span the entire width of the heap and continually travel back and forth, distributing the ore on the heap. A bucket-wheel excavator can be installed to remove the ore after leaching is complete. Several recent dynamic heap installations have been built in the form of a ring or oval with a moving "slot" from which the ore has been removed. Ore is removed on the advancing face of a slot and new ore is placed on the trailing edge. The "slot" can be seen in Figure 11.3-6 between the new ore stacked by a spreader conveyor on the right and leached ore removed by a bucket-wheel excavator on the left. The slot between old and new material with a short distance into each face of the heap for the two conveyors to work is the only area of the heap that cannot be under leach.

Mobile spreader conveyors up to 400 m long, mounted on multiple caterpillar tracks so they can travel in any direction, are used on multilift, very-high-tonnage heaps, with notable examples being in the Chilean copper industry.

Figure 11.3-5 Valley-fill heap leach at Ocampo, Mexico

SOLUTION COLLECTION

After the values have been dissolved, it is necessary to collect the pregnant solution. A wide variety of arrangements are used to collect the solution and direct it to the pregnant pond. On some valley-fill heap leaches, all of the solution is drained to a single point on the pad and directly into the pregnant liquor pond. As mentioned earlier, a portion of the solution may even be stored inside the void spaces in the heap, thereby minimizing the need for a large pregnant pond. Pregnant solution is usually collected in lined ditches that run adjacent to the heap. More than one inlet to the ditch may be used if it is desired to observe the recovery of different areas on the heap. To further increase the ability to watch the recoveries of different parts of the heap, small ridges may run the length of the leach pad, perpendicular to the collection ditch, to separate the heap into "cells." It is common for a weir to be placed at the point where the pregnant solution exits from each cell, or from the entire pad, to measure the flow draining from the heap. With a heap designed with cells, it is possible to segregate solutions into an intermediate pond. Multiple ditches or pipes run parallel to the heap, one running to each pond. Figure 11.3-7 illustrates this process at the Tarkwa heap leach in Ghana. The three large gray pipes on the right distribute the barren and intermediate leach solutions to each cell of the heap while the black pipes collect the intermediate and pregnant heap runoff solutions. The box at the base of the cell is a solution control point to select which solution will be used for leaching and to which pond the runoff will go. There is also a weir in the distribution box for an instantaneous measurement of solution from the heap. The pad below the heap is commonly a single plastic liner above compacted clay, but the ditches and ponds (and flooded areas of valley-fill heaps) are usually constructed with a double plastic liner with intermediate leak detection.

METALLURGICAL BALANCE

If the values available are not well tracked, the amount of recovery will never be known. The following are some of the values that are important to obtain to be able to calculate a good metallurgical balance:

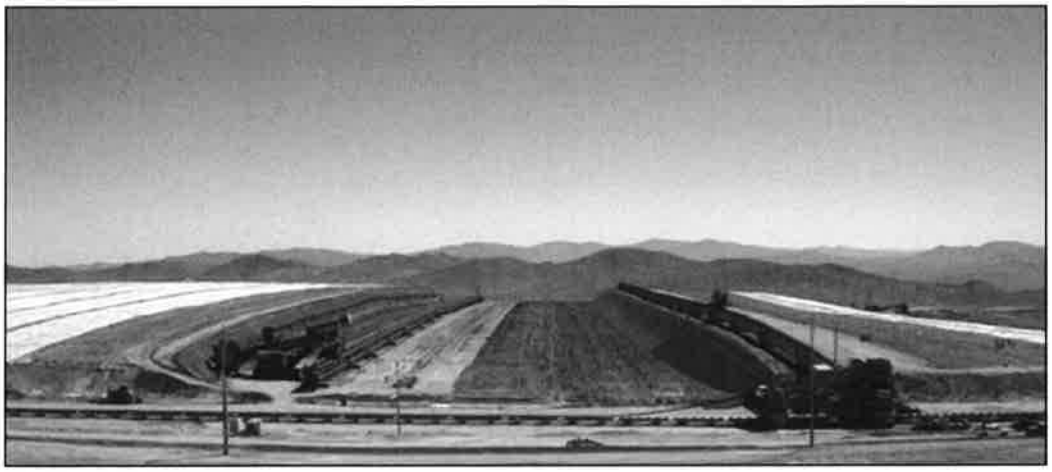
- Sampling of the ore to be stacked
- Knowing when, where, and how much ore is stacked
- Conducting quality column leach tests to monitor the continually changing ore, and modeling the test results to apply to the heap
- Sampling and flow measurement of the barren and pregnant solutions to and from the heap
- Good assay procedures employing fire assay of the ore samples for gold ores, and total and soluble copper assays for copper ores
- A good model that accounts for delays caused by adding lifts
- Patience

It is important to collect good grade, tonnage, and column test data from day one. It cannot be assumed that the entire ore body will act the same as the initial sample taken for design. To maintain a representative model, the recovery curves will change with the grade, ore type, variations of dilution from waste, and other factors that may affect the recovery. It is difficult to produce a stable and accurate metallurgical balance early in the life of a heap because of the slow reaction time. As a heap ages, the intricacies of how the permeability and leach rates of that particular heap will become easier to predict. A metallurgical balance is a continually changing tool for managing a heap and predicting the cash flow. A good model will keep bankers, stockholders, and your managers happy. A poor one can put a mine in dire straits when the predicted cash flow does not materialize.

DESIGN CONSIDERATIONS FOR RECLAMATION AND CLOSURE

After the heap leaching operation is completed, the facility must be closed in accordance with local environmental requirements. Closure activities are highly variable depending on the environmental sensitivity of the site and on the regulatory regime. In general, heaps are washed for a short period of time (commonly 3 years), during which time 1 t of wash water or recycled treated process solution per ton of ore is applied. Heaps are then capped, and ponds are filled and covered with suitable materials.

The easiest heaps to reclaim are single-lift heaps because the older heaps are abandoned early in the life of the operation and can be washed while production operations continue. In



Courtesy of FLSmidth RAHCO, Inc.

Figure 11.3-6 Slot between new ore (right) and leached ore (left)

Source: Kappes 2002.

Figure 11.3-7 Solution collection at the Tarkwa heap leach

valley-fill heap leaches, nearly all the ore ever placed on the pad is situated directly under active leach areas. Thus, washing of the entire heap must wait until operations are completed. Larger operations may have two or more valley-fill leach areas and can therefore appropriately schedule closure activities.

Environmental regulations usually applied in the United States call for reasonably complete washing of the heap to reduce pH, to remove cyanide, and to partially remove heavy metals. Cyanide is fairly easy to remove because it oxidizes naturally, but pH and heavy metals are more difficult to control. Regulators are recognizing that a better approach is to conduct a "limited" washing program and then to cap the heap with a clay cover and/or an "evapotranspiration" cover of breathable soil with an active growth of biomass. These covers are designed to prevent infiltration of water into the heap. After several years of active closure activities, the flow rate of the heap effluent decreases to a manageable level (or to zero in arid environments). After the flow rate has reached an acceptably low level, heap closure is accomplished by installing a facility for recycling collected effluent back to the heap. A relatively small "cash perpetuity bond" is maintained such that the interest on the bond covers the cost of maintaining and operating the intermittent pumping facility for as long as necessary.

Worldwide practices range from simple washing and abandonment to the more complex procedure described above. Environmental design is an industry unto itself, and the simplistic concepts discussed here may not be universally applicable. Heap closure needs to be addressed in the feasibility stage of the project.

TROUBLESHOOTING

As with most things in life, the best troubleshooting for a heap is to do it right the first time. One of the primary challenges in operating a heap is the delay in metallurgical response. With long leach times, the results of a change in operations will not be seen for months. A common mistake people make is to watch a heap on a day-by-day basis, which is an insignificant amount of time. Arguably the most critical time in the construction of a multilift heap is the base lift of the heap, when operators are least familiar with the equipment and the characteristics of the ore. If the first lift is built poorly and has poor permeability or chemistry, this can have a lasting effect throughout the life of the heap.

Permeability

When permeability problems arise, there are few options to improve it. Often the first sign of low permeability is puddles of standing water on the surface of the heap, called ponding. Apart from ripping the top couple of meters, there are few viable options, although several have been tried. Some heaps are rehandled to improve permeability, which may be profitable on a higher-grade heap as pockets of ore will not have leached. Heaps have also been blasted to try to "fluff up" the ore, though with limited success. Allowing the water to pond might help to force the solution through. Efforts to improve the permeability of already-stacked ore are typically cost prohibitive.

Stability

Low permeability can also cause the ore to become saturated with water and lead to stability issues. The primary cause of stability issues in a heap is the complete saturation of a structurally significant portion of the heap. At the first signs of solution discharge from the side of the heap (more than 1 m above the base) or small blowouts, it is best to stop leaching that area immediately and assess the problem. The problem may be a general issue of poor permeability, or it may be that during stacking of an upper lift, the top surface of the lower lift was made impermeable. If this problem occurs, it usually implies that there will be an overall loss of recovery in the entire heap. To solve the immediate problem, the only practical solution is to reduce leaching near the heap edge, but it is possible to drill the area for installation of vertical drains. The problem indicates that the operation must do a better job of agglomerating new ore, or of ripping and then limiting traffic on the surface below a new lift.

Liner Leaks

Most pads have leak detection pipes below the pad, and leaks will report to the secondary containment sump. Some leakage through the primary liner is generally permitted, but excessive leakage will require abandonment of the heap. Several geophysical technologies have been developed to help locate a hole in a liner, but their accuracy is limited to a circle on the pad with a diameter equal to the vertical height of the heap. It is expensive to repair a liner under an operating heap, as the simple act of exposing it can complicate the issue by creating more holes. It is critically important to prevent liner leaks during construction.

Poor Recovery

A common problem that a heap leach will run into is that the ore takes longer to leach than predicted by the laboratory tests. To eliminate this risk, heap leach design must allow for total flexibility to extend leach times. Many heaps, especially in the copper industry, have achieved economically acceptable performance even though leach times were very long.

It is common practice to minimize the use of cyanide on a heap to save money. In reality this can lose money if done incorrectly. Initial laboratory tests can indicate starting concentrations and operators may periodically explore different cyanide levels to see the effects on recovery. The problem with this approach is that the results of any changes in a heap take a long time to notice. A better approach is to maintain an active production support laboratory and to periodically run a series of parallel column leach tests at different cyanide addition levels to find the best addition concentration. The cyanide concentration in a heap is controlled by the addition of cyanide to the leach solution, but the cyanide in the pregnant solution coming from the heap should also be monitored.

Acid Production/pH

For cyanide heap leaches, lime is usually used to maintain a pH above 10. For ores that generate acid slowly, limestone can be blended in with the ore as well. Caustic can be used but is normally not economic and can result in chemical reactions that plug the heap or are detrimental to the recovery process. If the pH of the pregnant solution flowing from the heap drops because of the oxidation of pyrite and other sulfides, there is generally no economic remedy. Such acid zones should be watched carefully as they can cause gold loaded in upper lifts to precipitate. That area of the heap may have to be abandoned. Future ore should be stacked with the correct amount of pH modifier.

For copper heaps, H_2SO_4 can be generated by the ore itself, but in most heaps, extra acid must be added. However, it may be needed in such quantities as to make the availability of this reagent the key economic issue in evaluating the project.

CAPITAL AND OPERATING COSTS

Heap leaching normally has significant capital cost advantages over agitation leaching. The capital costs for a heap leach can vary widely, from $2,500 to $8,000 per daily metric ton of ore treated depending on many variables including, but not limited to, process rate, location, infrastructure, and company policy. The capital costs of a typical agitated leach circuit per daily ton of ore treated is up to eight times that of a typical heap leach.

Operating costs for an agitated leach circuit may be several times that of a heap. In other cases where a large amount of cement is required for agglomeration or where the ore needs to be fine-crushed, the operating costs of agitation leaching are not necessarily higher than for heap leaching. Heap leach operating costs are not very sensitive to the size of the operation because as some things get less expensive (i.e., general and administrative expenses), other things get more expensive (recovery plant operation). This relationship can be seen in Table 11.3-1.

CONCLUSION

Although the concepts of heap leaching are simple, the practices have substantially evolved over the past 40 years. Early choices for pad materials, sprinkler systems, and stacker designs have been discarded under the pressure of operating experience and cost-reduction factors. Overall operating costs have continually declined as "superfluous" activities and controls have been eliminated.

In spite of the apparent simplicity of the heap leach process—or perhaps because of it—there were many failures in the early years. Now there is a large number of successful operations from which to draw the experience needed to optimize the process. Heap leaching is expected to maintain its

Table 11.3-1 Heap leach operating cost distribution

Operation	3,000 t/d	15,000 t/d	30,000 t/d
Mining, %	27.8	26.0	24.2
Crushing, primary, %	3.7	2.6	2.9
Crushing, second plus third stage, %	4.6	5.1	2.9
Crushing, fourth stage, %	7.4	10.4	11.4
Agglomeration/stacking, %	1.9	1.3	1.4
Leach operations (including sprinkler supplies), %	4.6	3.9	2.9
Recovery plant operations, %	13.9	16.9	20.0
General site maintenance, %	5.6	3.9	4.3
Cement for agglomeration (10 kg/t), %	9.2	13.0	14.3
Cyanide, lime, other reagents, %	2.8	3.9	4.3
Environmental reclamation/closure, %	4.6	6.5	7.1
General and administrative, support expenses, %	13.9	6.5	4.3
Total operating costs, %	100	100	100
Total operating costs, $	10.80	7.70	7.00

place as one of the principal tools for extracting gold, silver, and copper from their ores for both large and small deposits. The challenge for the future will be to remember and apply the experiences of the past.

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