CHAPTER 10.3

Heap and Dump Leaching

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Heap leaching is a hydrometallurgical recovery process where broken ore of appropriate characteristics is stacked upon an engineered liner, and then the surface of the heap is irrigated with a water-based lixiviant. Leach solution travels through the ore under unsaturated fluid flow conditions, contacting and leaching the metal or mineral of interest. Solution exits the bottom of the heap through slotted pipes and a drainage gravel layer placed above the liner. The metal-rich pregnant leach solution (often termed *PLS* or simply the *preg*) is then collected by gravity and sent to a process facility for recovery of the metal values. The solution exiting the metal recovery section, referred to as *raffinate* in copper leaching or the *barren* in gold leaching, is refortified with the lixiviant chemicals and pumped to the top of the heap.

Heap leaching is often broken into two principle distinctions, run-of-mine or *ROM* dump leaching and crushed ore heap leaching. Dump leaching consists of truck end-dumping of ore broken only by the drilling and blasting of mining activity. After completion of ore placement, the surface is ripped using bulldozers to break up compaction layers and improve solution distribution uniformity.

Crushed ore heap leaching involves reducing ROM ore to a predetermined optimal target size distribution, sometimes with topsizes as small as 12.5 mm (0.5 in.) or even finer through multiple stages of crushing. Crushing increases surface area and mineral liberation which, in turn, result in higher, more economic recovery. Crushed ores are often agglomerated to bind fines and clays with the larger rocks then placed on the heap using mobile stacker conveyors to improve ore wetting, leaching, and solution percolation through the heap.

Following stacking and surface preparation, ore is irrigated using drip emitters or sprinklers to evenly apply leach solutions to the heap surface. For successful heap leach operations, the ore must be of high porosity or must be fractured to ensure thorough contact between the metal or mineral in question and the lixiviant/leach solution (Heinen and Porter 1969).

A simplistic heap leach flow sheet is illustrated in Figure 1. A unit of ore under irrigation is called a *cell*. Solution discharges from the cells to the pregnant or PLS pond. This pond typically has several backup solution or storm ponds to handle temporary solution surges from weather events. The heap leach process is designed to contain all solutions from the environment and recover the dissolved metal or mineral values.

For copper and other metal sulfide minerals, the heap leach process has evolved to incorporate bacteria and nutrients into the barren solution promoting the bio-oxidation of sulfides. Aeration of the heap is often required in these cases. Similar applications to heap leaching include in situ leaching, rubble leaching, and vat leaching. Refer to Chapter 10.4, "Vat Leaching," and Chapter 10.2, "Solution Mining and In Situ Leaching," for more detailed information.

Heap leach operations are found on all continents and are used to recover a wide variety of metals, principally copper, gold, and silver. Less commonly, other metals such as cobalt, nickel, uranium, and zinc are recovered. In 2006, 10% of the world's gold production (Marsden and House 2006) and 18% of the world's copper production (ICSG 2015) were produced from heap leaching.

The primary advantages of heap or dump leaching as compared to milling ores are

- Lower capital costs,
- Lower operating costs,
- No liquid/solid separation step, and
- No tailings disposal.

The primary disadvantages of heap or dump leaching as compared to milling are

- Lower metal recovery,
- Longer process time,
- Slow response to process changes, and
- No by-product credits.

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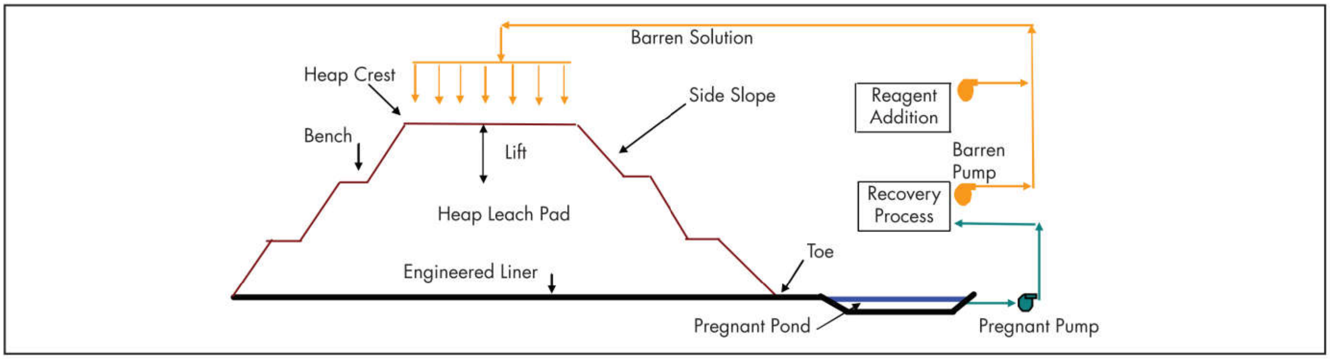


Figure 1 Simplistic heap leach flow sheet

FUNDAMENTALS

What appears to be a simple, empirical process has long been recognized as being very complex, involving many critical factors that encompass several scientific disciplines, such as physics, chemistry, geology, biology, and hydrology (Bhappu et al. 1969).

Dump leaching has mostly been applied to gold, silver, and copper ores, whereas heap leaching has been applied to many different minerals including copper, gold, silver, uranium, vanadium, zinc, nickel, and cobalt. However, as the principal applications are copper and precious metals, most of the following discussion will refer to these metals.

Five factors are essential to the successful heap leaching of any metal-bearing ore or valuable mineral:

1. A lixiviant must be selected to optimally dissolve the target valuable mineral and minimally dissolve gangue minerals.
2. The lixiviant diffuses to the site of the reaction.
3. A chemical reaction must occur.
4. The solution containing the dissolved metal or mineral must diffuse away from the reaction site and back into the main solution stream.
5. The dissolved target metal or mineral must be recoverable from the main pregnant solution.

In leaching a given ore, the rate of metal extraction can be rapid or slow depending on the mineralogy, lixiviant, and the chemical dissolution reaction. The factors of penetration, dissolution, and diffusion go on simultaneously and not in successive steps. The ore is wetted from the surface, and solution travels down through the heap due to gravity under variably saturated conditions as described by the Richards equation (Sullivan 1931) and characteristic curves (Van Genuchten 1980).

Percolation Theory

Leach solutions passing through a heap (and all flow regimes where unsaturated flow conditions exist) can be divided into three zones: the saturated zone (where all pores are filled with water), the unsaturated zone (where pores are only partially filled with water and that water is held in place by capillary forces), and the capillary fringe (where pores are filled with water being held in place by capillary forces). However, the flow regime is essentially composed of only the wide channels and macropores carrying large quantities of water by gravity flow (Bartlett 1993).

When rock is fragmented during mining and crushing, the bulk density of the material decreases with a resulting increase in void space. This *swell factor* can be 25%–40% by volume. On stacking and leaching, the ore settles/compacts with wetting and because of the weight of ore placed above it. Depending on the heap height and because of this compaction, the volume percent of voids in the bottom of the heap may be less than 5%. When the regional solution application rate is greater than the heap permeability, solution reaches a bottleneck and migrates horizontally until it reaches a region of better permeability to continue gravity flow downward.

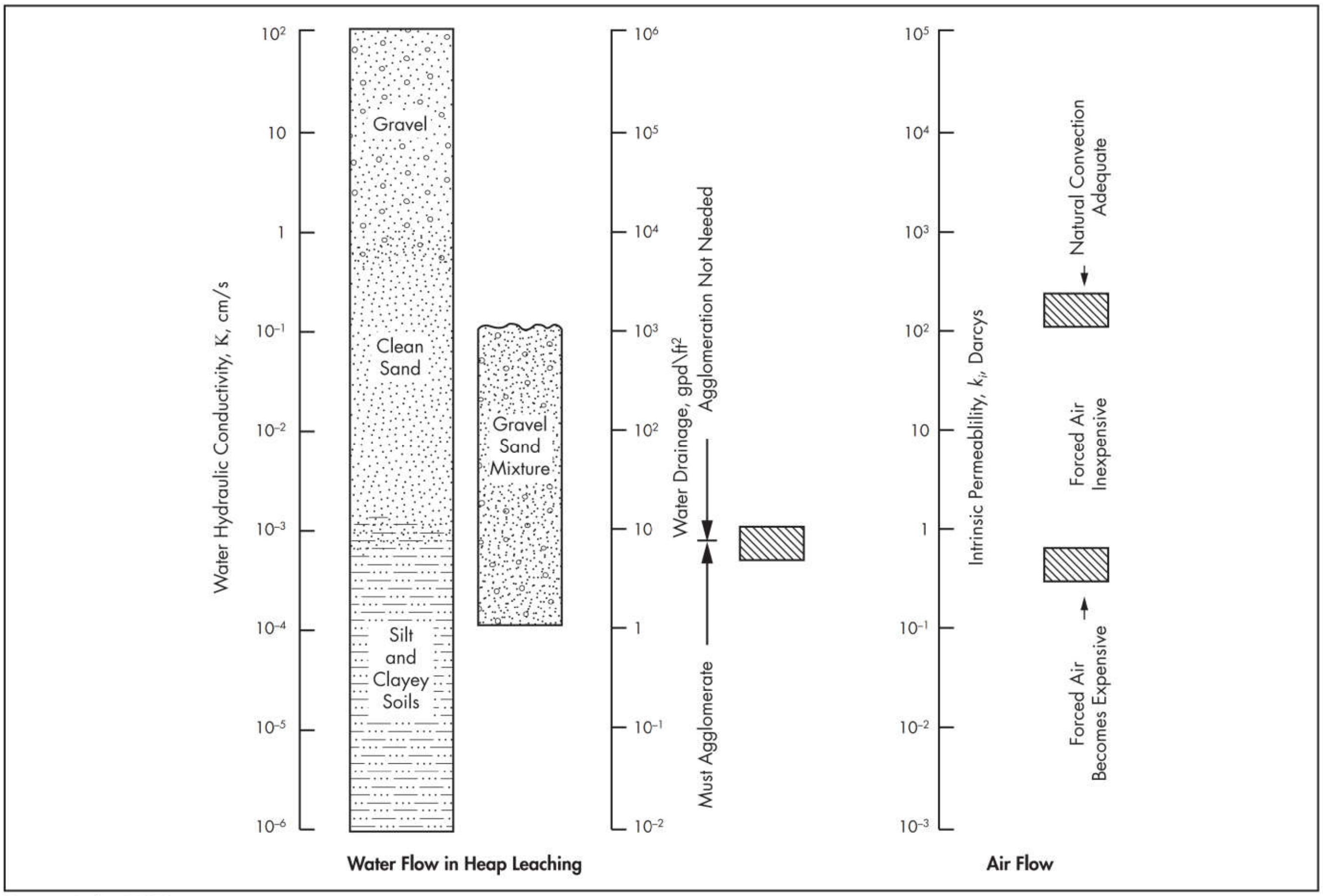
If a solution pathway is not available, the solution volume tends to build up, leading to surface ponding and internal *perched* water tables. These can promote heap instability. If near the edge of a heap, solution can *blow out* the side of the heap, resulting in erosion damage to side slopes.

Solution flowing to a more permeable zone results in channeling, with the potential to cause fines migration and dry zones under the bottlenecks. The factor controlling the liquid volume in a heap is the particle size distribution (PSD). Solution fills all voids from rock sizes less than 0.3 mm (48 mesh) with the exclusion of air and rock sizes coarser than 1 mm (10–20 mesh) where solution drainage is almost complete. Capillary forces rather than gravity flow prevail for finer particles (fines).

As ore gangue minerals react with leach solutions, degradation or decrepitation of rocks can occur, resulting in more fines being produced. These fines will change the regional permeability of the heap (Bartlett 1998).

Normal heap leach operations have a wide distribution of ore particle sizes and uneven ore mixing, so there will be a range of localized hydraulic conductivities and percolation flow velocities (Bartlett 1993; O'Kane et al. 1999; Orr 2002). Figure 2 presents the ranges of water conductivity, water drainage, and air permeability for various particle sizes, ranging from clays to sand to gravel (Bartlett 1993). Thus, large variations in hydraulic conductivity (permeability), in combination with high solution application, will result in significant flow channeling ultimately leading to diluted pregnant solution grades and overall longer leach periods to target extraction (Bouffard and Dixon 2000).

Clays and significant fines content in ores pose the highest threat to suitable heap permeability and metal extraction efficiency. Poor permeability is the key factor in many failed heap leach operations. Agglomeration and appropriate stacking techniques obviate the clays/fines issues. Chapter 10.1,



Source: Barlett 1993

Figure 2 Effect of grain size on saturated hydraulic conductivity

"Agglomeration Pretreatment," presents the issues related to this pretreatment step.

Leach Chemistry

Leach chemistry factors and issues that must be considered for successful heap leaching of gold and copper are provided in the chapters on gold, silver, and copper hydrometallurgy elsewhere in this handbook.

Other metals of interest in heap or dump leaching include uranium, nickel, cobalt, zinc, and recently, some rare earth elements. Of these, uranium heap leaching has had the most attention. Because of its many oxidation states, there are numerous complex uranium minerals (Merritt 1971). Some uranium minerals can be leached with sulfuric acid or in alkaline conditions employing sodium carbonate. More-complex/less-oxidized uranium minerals require stronger acid and sometimes higher temperatures.

Heap leaching of nickel laterite ores using sulfuric acid was advanced during the recent commodities boom period of 2007–2013. The Talvivaara nickel bioleach operation in Finland (Saari and Riekkola-Vanhanent 2012) is currently processing ores containing nickel sulfide (pentlandite). Cobalt is recovered when heap leaching nickel–cobalt or copper–cobalt ores.

LEACH PADS

The leach pad itself is a key element of the heap or dump leach process. Selection of the type of leach pad, detailed pad design, liner selection, construction techniques, and assessment of geotechnical risks are all part of the overall leach pad development process.

Types of Leach Pad

Three main types of leach pads are used in heap and dump leaching. These include flat or expanding pads, valley fill pads, and on/off leach pads. Selection of pad type is influenced by many variables, including available topography, leach cycles, closure issues, and so forth. The choice of pad type influences capital costs, stacking options, solution application methodology, solution collection, recovery plant sizing, and closure issues.

Flat or Expanding Leach Pad

The ideal leach pad is located within a sufficiently large area with a 2%–3% downslope and 1% across slope, clayey in situ material below the topsoil, nearby sources of clay or low-permeability soil for the pad base, and gravel for the protective/drainage layer. This allows construction of a regular-shaped (rectangular) *flat* leach pad that can be stacked easily with mobile conveyor systems and expanded in the upslope direction at a relatively low installation cost. Solution collection and storage systems that form key aspects of the overall project are also straightforward regarding design, construction, and utility.

In reality, very few mine sites cooperate to the extent that all these factors are favorable. Slopes can be as low as 1% downslope or quite high (up to 20%) with rocky ground, no available clays or gravels, and so forth. Expanding pads, however, offer the most overall cost benefits and ease of operation. Thus, most leach pads are built as expanding pads even though the "flat" identifier may not be accurate.

Collection systems incorporating individual leach cell outlets and collection ditches or pipes can likewise be expanded upslope with the pad. Process ponds can be located logically and sized for the life of the operation. Stormwater pond capacity may need to be increased as the leach pad expands.

Expanding pads with multiple cell outlets also offer greater flexibility in multistage leaching, with recycling of low tenor intermediate leach solution (ILS) onto newer ore to maintain upgraded PLS, which is treated at a constant flow rate over the project life.

Expanding pads offer relatively easy access for stacking of upper lifts. In this case, when the first lift of the initial leach pad is completed, the decision to go up or go out needs to be made. This is usually based on cost factors, which often indicate going up rather than building new pads. Operability issues, such as long leach cycles, increased metal inventories in multiple lifts, and risks of channeling may force an expansion of the leach pad prior to building upper lifts.

Valley Fill Pads

Valley fill pads are built in areas of steep terrain where large, flat areas are not available. A valley fill pad usually consists of constructing a dam across a suitable valley, with ore stacked behind the dam as shown in Figure 3. The dam wall and downslope leach pad area form an internal solution collection/storage pond, and the natural topography directs solutions to the pond. Steep walls of the valley and dam offer potential difficulties in pad preparation and liner installation.

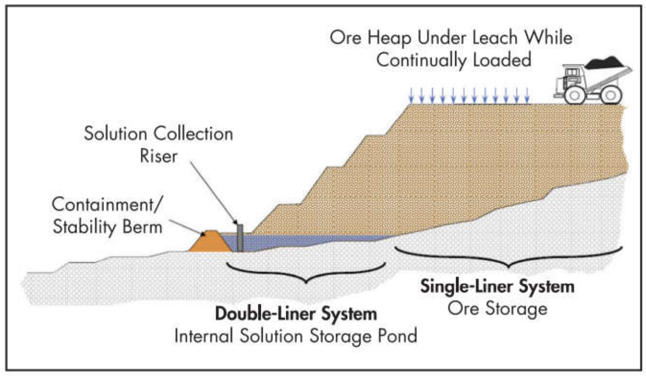
As ore is stacked in multiple lifts, the lining is extended up the valley. Valley fill lifts are more appropriately stacked with trucks or with an advancing conveyor stacking system that operates on top of the lift rather than on the relatively steep base. Softer, more compressible ores should perhaps be avoided in a valley fill heap.

A valley fill pad can be designed to contain all process solutions as well as incident rainfall. Otherwise there can be external stormwater ponds connected by a spillway from the internal pond.

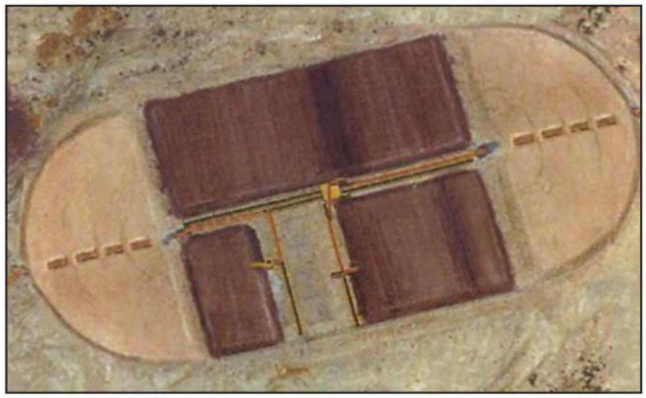
The main disadvantages of valley fill pads are higher cost of installation, reduced leaching flexibility with a single process pond, and often a requirement for staged increases in solution treatment facilities. The latter is caused by falling PLS grades as the pad expands and rainfall dilution cannot be diverted away from the internal pond.

On/Off Pads

The on/off leach pad concept employs a permanent, fixed-size leach pad. Ore is stacked, leached, rinsed, then removed either to a separate stockpile where it is abandoned or to a secondary leach pad where leaching continues. Several smaller on/off gold heap leach operations have been built (Bernard 1995). Currently, several very large copper heap leach operations in Chile employ on/off leaching systems (Taylor 2017).



Source: Galea et al. 2010
Figure 3 Valley fill leach system



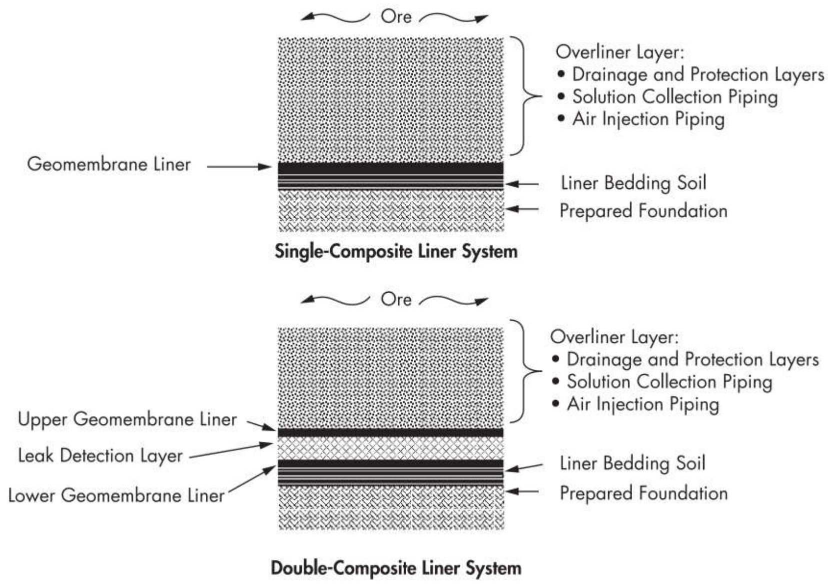
Courtesy of FLSmidth
Figure 4 Racetrack on/off leach pad

The on/off concept is most useful for relatively fast-leaching ores (generally 30 days or less), in areas with limited available leach pad area or in high-rainfall environments as the combined pad/pond collection area is minimized.

Some large heap leach operations employ a *racetrack* arrangement, employing mechanized stacking and unloading systems that can move large volumes of ore quickly and at reduced operating costs (although upfront capital costs are high for these systems). See Figure 4. The leach pad is constructed in two parallel sections with stacking equipment advancing across one section before rotating around to stack on the opposite section. The reclaiming system follows a similar pattern, removing leached/washed material.

Solution collection systems can be directed either to the center section between the two pads or to the outer sides of each pad. The pads are subdivided into cells with separate, dedicated collection systems directing off-flows to ILS or PLS ponds.

The leach pad base must be able to withstand vehicle traffic on a routine basis so is more robust than a typical flat pad. Pads are often made of layered asphalt with an impervious rubberized layer, concrete, or standard composite clay/high-density polyethylene (HDPE) but with thick protective gravel layers.



Source: Galea et al. 2010
Figure 5 Typical liner construction

One advantage for on/off operations is the capability to collect representative tailings (*ripios*) samples during pad unloading for a more reliable metallurgical balance and heap recovery assessment. Another advantage is the relatively small amount of unrecoverable gold-in-inventory (gold dissolved in solution remaining within the ripios) compared to multiple lift heaps.

The main disadvantages include high capital cost, higher operating costs caused by double handling of material, and a limit to leach times available. In the latter case, leach cycles required to achieve optimal recovery may not be available as the requirement for getting new ore under leach to maintain cash flow overrides the relatively minimal additional recovery.

Pad and Pond Design and Construction

Constructing a heap leach pad or pond system begins with obtaining the necessary federal, state, and local permits based on the development of a feasibility-level engineering design. These permits are numerous, cover areas addressing land access through to reclamation plans, and vary depending on location and land title. Prior to the permit application, the heap leach facility needs to be designed for size, location, and ore stacking/treatment rate, with detailed solution management and reclamation plans.

The heap leach pad design is conducted by a professional engineer. The design areas include crushed and/or ROM ore rock properties; seismic data for pad stability; water balance and solution management; pad, pond, and solution piping containment and monitoring; heap height; future expansion; and reclamation and closure plans. A site investigation by a geotechnical engineer is often required to assess construction issues, suitability of available in situ and borrow materials, surface runoff conditions, groundwater or seepages, and other issues that may impact construction costs and timing as well as the stability of the heap or dump during operations. Figure 5 presents the most typical liner systems in use in modern heap and dump leach design. The single liner system is generally acceptable in most jurisdictions.

Monitoring systems are incorporated to monitor for leaks in the pad or ponds. Additional leak detection methods may be required, which could involve a collection system under the geomembrane or between geomembrane layers daylighting in the downslope collection ditch for continuous monitoring.

The greatest cost in heap leach pad construction is the foundation earthworks necessary to provide the firm, stable loading surface. The pad must be sufficiently level so that it is possible to line with geomembrane and, if specified in the design criteria, be operable for a retreat-type mobile stacker (approximately 6% maximum gradient). The pad must also have surface area necessary to meet leach cycle requirements on the next to last lift.

Cutting and filling of the leach pad and pond area are performed by mine equipment and construction equipment alike, depending on fleet availability and any spatial constraints involved in foundation preparation usually dictated by subsurface geotechnical conditions, topography, and geomorphology. The base is then covered with approximately 300 mm (12 in.) of compacted soil of low permeability and lined with a geosynthetic liner such as HDPE or linear low-density polyethylene (LLDPE).

In areas where clay is unavailable, bentonite-impregnated geotextile known as *geosynthetic clay liner* or GCL has been used to form the low-permeability layer. GCL is also used on steeper slopes where compaction equipment cannot be safely operated. In all cases, a geotechnical evaluation of the composite liner system is necessary to ensure overall heap stability. The key aspects of leach pad design are discussed by Thiel and Smith (2004) and Breitenbach (2005).

Specifications for permeability of the clay base are normally 1×10^{-6} to 1×10^{-8} cm/s. Quality control testing of the clay layer is required during placement. More information on liner selection and installation is provided by Breitenbach (1994, 2004).

A protective cushion layer of ~300 mm (~12 in.) of compacted soil or clay is often installed on the geomembrane to provide protection from vehicular traffic. Then a network of perforated drainage pipe is laid on top of the liner or the cushion layer. The collection network is designed to provide sufficient flow-carrying capacity to a point of collection. This speeds collection of pregnant solutions and minimizes hydraulic head on the liner thereby limiting risk of any leaked solution from migrating beneath the pad and into the environment.

Finally, the network is covered with a free-draining overliner rock material, often ore crushed to a coarse gravel size distribution of –50 mm (–2 in.). If no bedding layer is installed over the geomembrane, then the drainage gravel topsize should be –12 mm (approximately –0.5 in.), or finer if the crushed rock is particularly angular. A layer of geotextile fabric over the geomembrane could be installed thus allowing coarser or more angular drain rock. Heap stability may be compromised when using geotextile over geomembrane for steeper leach pads.

Containment berms around the perimeter of the heap are necessary to keep leach solutions in the system and to prevent surface runoff from entering the system. These are usually constructed from compacted soil and are overlain with geomembrane as an integral part of the pad liner. Berm heights of 0.5–1.0 m (1.6–3.3 ft) are employed for internal dividing berms as well as for external berms along the top and ends of the pad. The main berm along the downslope edge where solution collection ditches and pipes are located can be much higher to ensure that any heap slumping does not impact on solution collection.

Generally, solution ponds containing process solutions (cyanide for gold/silver, acid for copper, etc.) are built using the same procedures as leach pads, but often with double geomembrane liners with leak detection monitoring systems incorporated under each liner layer. Stormwater ponds or raw water ponds not expected to routinely contain lixiviant chemicals are usually built with a single geomembrane liner.

Process ponds are usually built as rectangular designs with a low corner or sump to allow most of the solution to be pumped out. The leak detection system is placed under the sump. Pond wall slopes of 3H:1V are typical as steeper walls are difficult to adequately compact. An allowance is made in volume calculations for spillways and freeboard. Ponds are often fenced and netted or covered with bird balls to reduce wildlife exposure and evaporative losses.

A typical pond system will have interconnecting overflow spillways such that the entire pond system fills before any solution overflows to the environment. Emergency unlined catchments may also be part of the overall solution management system.

The geomembrane liners for berms, ditches, and ponds are often textured to reduce slipping hazards if significant foot traffic is expected in the area. Often, liners under the ore and in areas not continually exposed to sunlight are thinner at 1.0–1.5 mm for HDPE and LLDPE while exposed areas and areas with high foot traffic are thicker, usually at 1.5–2.0 mm.

A key part of the approach to pad and pond design is a geotechnical evaluation of the leach pad/pond sites for overall suitability. This includes assessment of available construction materials for preparation of the base foundation, the low-permeability layer, and any overliner materials. Evaluation of the ore stacking plan is required to ensure pad stability over the life of the operation and beyond.

The ultimate height of the heap is established by evaluation of several primary constraints:

- Liner and drainage system integrity with increasing load
- Intrinsic ore characteristics governing permeability reductions with height (geomechanical aspects)
- Seismic conditions in the area
- Heap stability based on the interfaces between ore and the liner system
- Slope stability under various conditions of saturation

Prior to construction, surface water diversion channels are cut around the pad/ponds to direct surface runoff away from the area under construction, protect process facilities during operations, and limit water balance impacts.

ORE PREPARATION

Prior to placement of ore onto the leach pad, some ore preparation is usually required. This can include addition of pH control chemicals (usually lime for gold/silver), crushing, agglomeration, screen upgrading, and so forth. The initial preparation step in the leaching process is mining, which is common to all approaches.

Blasting to increase fines generation, or sometimes to limit fines generation, followed by dozing, loading, hauling, and tipping onto the pad or into feed stockpiles can affect processing and leaching performance. Some degree of blending can be accomplished in the pit. The mining approach can also have a major impact on the moisture level of feed ores, which affects downstream handling properties.

Otherwise, the choice of ROM dump leaching versus crushed heap leaching is usually a question of economics where many variables such as extraction, reagent consumption, assumed metal price, project life, capital expense, and operating expense are considered.

Run of Mine

Dump leaching to process ROM ore is affected by the size distribution of the feed ore because reagent consumptions and metal extraction are often impacted by the exposed surface area of the material being leached. Thus, finer blasting may improve leach results while avoiding the additional capital and operating costs of a crushing operation.

For gold and silver operations, leaching pH is often controlled through addition of quicklime or hydrated lime to the ore prior to stacking, usually by dosing lime onto the ore in the back of the haul truck at a lime-dosing station. Other methods of lime dosing include dosing the empty truck as it returns from the pad, spraying a lime slurry onto the ore either in the haul truck or as it is dumped on the pad, or adding bagged lime onto the ore in the pit prior to/during mining. The latter approach is most suitable to very small operations.

There is no easy method of adding acid during stacking when dump leaching copper or other ores using sulfuric acid as lixiviant.

Crushing

Leach extraction generally increases as material is reduced in size, thus liberating the target mineral for leaching. Size reduction is generally accomplished through standard crushing techniques, although recently, more heap leach projects are considering finer crushing incorporating vertical shaft impactors (VSIs), high-pressure grinding rolls (HPGRs), or quad roll crushers. After primary crushing, ore is often screened to remove fines and avoid the recrushing of this size fraction.

VSI machines have been employed to crush heap leach ores as fine as 2.36 mm (8 mesh) (Rose et al. 1990). HPGR crushing to as fine as 4 mm (0.16 in.) has been evaluated at a laboratory scale. Gold Fields' Tarkwa mine employed an HPGR unit for heap leach feed at a crush size of P_{50} 3 mm (0.12 in.), treating some 4.4 Mt/yr (4.8 million stpy [short tons per year]). Golden Queen Mining's Soledad Mountain operation uses an HPGR to produce a product with P_{70} of 6 mm (0.24 in.). Improvements in gold recovery of up to 10% over standard crushing circuit product have been reported (McNab 2006; Von Michaelis 2009).

Although agglomeration, as discussed next, is not required for all crushed ores, addition of pH modifiers and/or lixiviants during crushing/stacking can give a head start to leaching of the desired metal. Lime or cement in dry form as well as cyanide solution can be added to gold/silver ores on the product conveyor, and sulfuric acid can be dosed to ore on a conveyor belt or at a transfer point. Care must be taken to prevent spills or leaks of hazardous solutions from conveyors onto unlined/uncontained areas.

Agglomeration

Agglomeration improves ore permeability to both air and liquids by eliminating segregation of fines, resulting in a more uniform heap. Well-operated agglomeration also allows for improved reagent and solution addition to ore. Controlled reagent addition has obvious cost benefits, while controlled solution addition also results in drier agglomerates, which are less likely to plug chutes.

Moisture addition can play a key role in optimizing agglomerate quality, and this is especially true with cement agglomeration (Pyper et al. 2015). Unfortunately the wetter, sticky agglomerates can impact downstream conveying operations.

Agglomeration quality control is often visually done. Techniques involving measurement of electrical conductivity have been successfully used for agglomeration process control (Velarde 2003; Bouffard 2005), and infrared and microwave moisture analyzers have been employed for controlling solution addition. Otherwise, many operations control agglomerating reagent feeders and solution additions through a ratio setpoint controller linked to the feed rate of material into the agglomerating drum.

Most operations employ rotating drums for agglomerating, as this is generally the most effective method of blending in reagents and forming strong agglomerates. However, belt and stockpile agglomeration can be considered (Chamberlin 1986).

The key factors in drum agglomeration are residence time and the volume of material in the drum as a percentage of total volume. A detailed discussion of drum agglomeration design and selection can be found in Miller (2005).

Blending

Blending strategies are incorporated for maintaining relatively uniform grade, ore characteristics, or moisture content of material fed to the heap leach. Clayey ores are often blended with rockier ores to assist in maintaining crushing plant throughput and possibly obviating the need for an agglomeration step.

Pulp Agglomeration

Pulp agglomeration (Zaebst 1994; Jones 2000) can be considered when there are relatively small volumes of higher grade ore in the ore reserve. The high-grade material is selectively mined and ground in a small grinding circuit. The ground slurry can then be leached in an agitated tank or blended in with lower-grade ore in the agglomeration system prior to stacking and heap leaching. If slurry volumes are low, they can be pumped directly to agglomeration; otherwise, they can be filtered with the cake added to the agglomeration feed.

STACKING

The three main methods for stacking heap leach ore include truck stacking, conveyor stacking, and excavator stacking. Truck and excavator stacking can be employed for dump leaching. In any case, the leach pad design must take into consideration the stacking approach.

Truck Stacking

Truck stacking is the most common method of stacking for dump leaching and is also employed at heap leach operations with competent, low clay/fines ores. Many operations employ dump construction techniques essentially identical to waste dump construction and maintenance, including watering of haul/access roadways on the dump to control dust. In these cases, compaction and breakdown of surface ore can be significant.

Alternate truck stacking scenarios can be employed where truck traffic is limited to dedicated roadways on the dump surface (Chamberlin 1981). Ripping is nearly always recommended after truck stacking. Studies have shown that compaction is usually limited to 1.0–2.0 m (3.3–6.6 ft) by normal mining truck traffic. Single pass or cross-ripping can be considered.

Conveyor Stacking

Conveyor stacking systems are common in heap leach operations and often include one or more overland conveyors connecting the crushing plant to the leach pad. Usually a tripper conveyor diverts ore from the overland running along the upslope edge of the leach pad onto a string of portable grasshopper conveyors that ultimately feed a radial stacker conveyor. Often a horizontal indexing conveyor feeds the stacker, and the stacker has a stinger conveyor extension on the end that can extend several meters. Both of these approaches reduce the number of relocations of the system (Figure 6).

Grasshopper stacker systems can operate in either retreat or advance mode. Most grasshopper-type stacking systems operate in retreat mode where the stacker operates on the leach pad base or on top of an older lift, stacking new ore in lifts from 6- to 12-m (20- to 40-ft) tall. In this case, the pad base/lower lift surface must be relatively flat and firm to allow the equipment to be relocated easily.

For upper lift stacking, compaction from the stacking equipment can be significant, and it is recommended that equipment have low ground pressure. This is accomplished either through minimizing the weight of the equipment or employing wide tires, tracks, or skids to spread the weight over a larger area.

Minimizing weight is difficult for stackers required to stack above 6 m (20 ft) in height and for high-tonnage

Figure 6 Grasshopper stacking system

operations where the equipment is large and must be robust and long lasting. Thus, radial stackers with tires often have high ground pressures and can sink into the operating surface, causing problems with both radial and towing movements. A grader or dozer is employed to rip the surface where the radial stacker has been operating.

For retreat stacking, the ore is stacked from the bottom (low end) of the leach pad with the stacking gear retreating upslope. As new lift surface is created, it is placed under leach with no impact on continued stacking operations.

Advance stacking essentially employs the same equipment as retreat stacking, but operates on top of the newly generated leach pad surface. The stacking system is extended through addition of grasshopper conveyors until the entire lift is completed. Advance stacking has the advantage of allowing a lighter stacker conveyor as it does not have to lift ore to any height. And it can build lifts over uneven or steep terrain, leaving a flat surface for the next lift. The main disadvantage is interference of the equipment (and related access roadways) with leaching activities. See Cook and Kappes (2013).

Track-mounted mobile stacking systems operating on a racetrack on/off leach pad or for large multiple lift operations are more automated and generate very flat surfaces (Figure 7). Mobile conveyor stacking systems offer low operating costs, which are offset by high capital expenditure.

Excavator Stacking

Excavator stacking can be employed for crushed or ROM ore and is considered when truck traffic on the surface of the new lift is expected to be problematic for permeability (Figure 8). The ore is delivered by haul trucks to the toe of the lift being stacked. Like truck stacking, it is a higher operating expenditure (OPEX) and lower capital expenditure (CAPEX) option compared to purchase of a conveyor system.

LEACHING

For theoretical aspects of the leaching processes for the relevant metals, refer to applicable chapters in this handbook. The practical aspects of solution application to heaps and dumps are covered in the following sections.

Figure 7 Mobile stacker at on/off heap leach

Figure 8 Excavator stacking a 5-m (16-ft) heap

Irrigation

Operational solution application (*leaching*) can be conducted employing a variety of sprinkler and drip emitter systems. Sprinkler systems are constructed principally from polyvinyl chloride or HDPE plastic because of light weight, low cost, ease of installation, and corrosion-resistant properties. Dripper lines are generally HDPE.

The goal of solution application is to have uniform surface coverage to allow for optimum wetting uniformity leading to maximal metal extraction. To minimize surface ponding, the application rate should match or be less than the hydraulic conductivity or acceptance rate of the ore. Solution application rates vary from 2.4 to 19.6 L/h/m^2 (0.001 to 0.008 gpm/ft^2) with typical applicate rates of 8–12 L/h/m^2 (0.003–0.005 gpm/ft^2).

The application method has been shown to significantly affect copper dump leaching effectiveness (Jackson and Ream 1980; Schlitt 1984; Uhrie 1998). Drip emitters are believed to be able to deliver solution more precisely than other application methods. They apply relatively large drops of leach

Source: Galea et al. 2010
Figure 9 Heap leaching solution application methods

solution directly to the heap/dump surface and also have the advantage of minimizing evaporation losses of both solution and reagents. Emitters also provide constant flow under a wide range of pressures (34–20 kPa, 5–30 psig). Emitter flow and spacing determine the application rate. The advantages of drip emitters are further delineated in Dixon et al. (2012).

Application methods are shown in Figure 9. Wobblers, D-ring sprinklers, rotating impact sprinklers, and misters are also used. Wind-borne losses from sprinklers and misters involve loss of reagents and potential environmental issues (Jackson et al. 1979). Pressure regulators employed in the sprinkler system can limit uneven coverage and wind loss issues related to pressure.

Solution Control

Leach pads are usually divided into cells or bays to separate leach solution off-flows from different blocks of ore for leach management, metallurgical accounting, and reconciliation purposes. For ores with long leach cycles or for large tonnage operations, use of multistage leaching is employed to provide additional leach time while limiting the size of the recovery plant capacity. Older ore is leached with barren solution from the recovery plant, and off-flow from this ore is recycled onto new ores, with the upgraded PLS then treated for metal removal.

Typically a two-stage, countercurrent leach regime is employed with ILS recycled to new ore. Three-stage leaching has been practiced at several operations where barren leach solution (BLS) is pumped to the oldest ore, ILS off-flow is then pumped to partially leached ore with off-flow recycle leach solution (RLS) ultimately pumped to the newest ore (Lawry et al. 1994).

One disadvantage of multistage leaching is an increase in the metal in inventory. Because of the delays in metal recovery (and related cash flow) from multiple lift heaps or dumps, considerations have been made for full or partial interlift lining systems (Echeverria et al. 2015). For a full interlift liner, the lower lift surface is graded and compacted, then a geomembrane is installed along with drainage pipe and drain rock. Solution is collected and directed down the face of the lower lifts to the cell outlet. If the lower lift ore is particularly clayey, compaction of the surface material to a low-permeability layer may obviate the use of the geomembrane.

As environmental standards become more stringent, water management procedures become critical to managing the heap leaching operation. Water management may include using different application methods to maximize or minimize evaporation, installing purpose-built evaporators and geomembrane "raincoats" on top or side slope surfaces to divert rainwater out of the collection system (Breitenbach and Smith 2007; Manning and Kappes 2016).

Side Slopes

Leaching side slopes of a heap or dump presents specific problems and is generally less effective, with metal extraction from side slope ore likely to be compromised. Neither sprinklers nor drip emitters present foolproof options for side slope leaching. Small sprinklers with a gentle sprinkling pattern offer a reasonable compromise for side slope leaching.

PONDS AND SOLUTION STORAGE

Solution containment is a key aspect of heap leaching. The vast majority of operations employ geomembrane-lined ponds to contain process solutions. A typical heap leach operation would involve PLS, BLS (or raffinate), and stormwater ponds. ILS/RLS ponds are required if multiple-stage leaching is employed.

For operations incorporating solvent extraction for metal recovery, settling ponds allow solids to settle out prior to treatment. Raw water for makeup is often stored in ponds, and there may be other lined process ponds involved with the metal recovery steps.

In areas of migratory bird flightpaths and where severe winters are encountered, solution tanks are often substituted for process ponds while lined stormwater or event ponds are employed for emergency containment. Several operations in Kazakhstan and Russia employ belowground process solution tanks for freeze protection. The tank option reduces flexibility in solution management but can force improved operational efficiencies.

Process pond sizing usually incorporates the following factors:

- Minimum leach solution pumping allowance (12 or 24 hours of operation)
- An allowance for draindown solution from active leach areas in the event of a power failure
- A minimum volume for pump operation/priming
- An allowance for nominal rainfall events that may occur a few times in a normal year
- Freeboard/spillway allowance

Stormwater pond sizing is based on a design rainfall event, such as a 1-in-100 year, 24-hour rainfall event over the entire catchment area (pad, ponds, and ditches). The design event is dictated by local conditions as well as regulatory guidelines. Experience shows that stormwater ponds that are designed for only the 1-in-100 year, 24-hour event will most likely fill and overflow at least once during a project life. Accumulation of longer-term extreme precipitation events should also be taken into consideration.

Given that leach pads are often built in stages, stormwater capacity has to match the rainfall requirements from the pad extensions. Often the initial stormwater pond capacity is sized for the initial installation plus the first expansion, with additional stormwater capacity added at the same time as the second pad expansion. A runoff coefficient is often included in pond sizing for the expected rainfall collected on active or inactive cells of the leach pad.

SAMPLE SELECTION AND TESTING

Ore samples for metallurgical evaluations are typically chosen in a collaborative process involving geologists, metallurgists, and mine modelers/planners. Geometallurgical domains and ore classification criteria are identified to reflect the deposit characteristics and variability (Olson Hoal et al. 2013). The ore body must be broken down into categories covering process-significant variables appropriate for the type of deposit being sampled. These include

- Oxidation state,
- Ore grade,
- Depth,
- Rock unit or lithology,
- Alteration/weathering, and
- Sulfide and gangue mineralogy.

Surface grab samples should be avoided. Near-surface bulk oxide samples can be of limited use for oxide deposits with respect to oxidation state, friability, and so forth, but should be used sparingly and in no instance be given any greater influence than a typical variability composite sample taken from drill core.

Variables to Evaluate

The cataloging of drill-core samples generates a table of composites representing various characteristics of the ores to be leached. Testing programs follow on from these composite selections but with these additional variables to be evaluated:

- Crush size/size distribution
- Spatial distribution within the ore zones (e.g., east end vs. west end)

Of key importance to the leach process is crush size/size distribution. Higher and faster extractions are expected at finer crush sizes, but the additional extraction may not be sufficient to offset CAPEX and OPEX for crushing, agglomeration, and conveyor stacking steps, in which case ROM ore dump leaching is the selected approach.

Types of Tests for Heap Leach Evaluation

The types of tests that are typically employed in assessing the amenability of an ore body to heap leach processing are

- Quick leach,
- Bottle roll on ground or pulverized ore,
- Bottle roll on coarse-crushed samples,
- Agglomeration,
- Screen analyses with fraction assays,
- Bench columns,
- Large columns and cribs, and
- Field trials.

The quick leach test (QLT) can be used for early identification of heap or dump leach potential. The main evaluation approach for heap leaching is the column test. However, shorter-term bottle roll leach tests have found a niche in the testing program to provide comparative data for variability samples and sometimes for crush size in a shorter time frame and at lower costs than column testing.

A ground ore bottle roll test (BRT) over a 24- or 48-hour leach period is usually conducted at a PSD with a P_{80} of ~75 µm (200 mesh) employing a pertinent leaching reagent regime. This basically gives the near-maximum metal extraction that could be expected from an ore in a milling situation. The results should mirror the quick leach results and are used to compare extractions from coarser size distributions. The BRTs can be conducted for kinetic evaluations with solution samples at 2, 4, 8, and 24 hours to assess the rate of leaching and to adjust leach chemistry.

Coarse ore BRTs are usually conducted on 2- to 5-kg (4.4- to 11-lb) portions of ore crushed to a specific size distribution or topsize, with rolling conducted on an intermittent basis of 30 to 60 seconds per hour. The intermittent rolling allows improved contact of the ore with leach solutions and air/oxygen but reduces the grinding effect of continuous rolling (and potential increased liberation). Intermittent bottle roll tests (IBRTs) are typically conducted for 4 to 10 days at 30%–50% solids with solution samples at logical intervals to determine leach kinetics and adjust leach chemistry.

One drawback of the IBRT is the relatively short leach time in comparison with column or field leaching. Thus for slow leaching gold/silver ores or some copper minerals, the IBRT may not be useful. Another drawback of the IBRT is the buildup of chemical species in the leach solution. This does not simulate heap leaching where ore is subjected to fresh leach solution on a continual basis.

Also part of the IBRT is a size analysis of the test residue, with metal assays on three to five fractions. This might indicate that all fractions leach to the same value, thus suggesting that a coarser crush size could be considered. Or it could show that there is a finer fraction size where extraction increases significantly. This break point can direct future test work at a finer crush size. IBRTs will give an indication of extraction as well as reagent consumptions/requirements but not geomechanical aspects.

Prior to column testing, an assessment of ore permeability should be conducted to determine whether agglomeration is required. A typical approach is a version of a falling head permeability test used in soils analysis. More involved geotechnical evaluation including triaxial testing can be used, but the simpler test is usually sufficient to determine the requirement for field agglomeration.

Otherwise, the clay/fines content in the material can be assessed, where ≥10% –75 µm generally indicates that agglomeration would be required (Chamberlin 1986). A detailed assessment of the hydrodynamics of stacked ore is presented in Robertson et al. (2013).

If agglomeration is deemed necessary, laboratory agglomeration in a cement mixer or on a rolling cloth is required to optimize conditions. A grid of three or more small (3–4 kg [6.6–8.8 lb]) batch tests at different binder levels and/or water additions should be set up for each ore composite, with agglomerated samples allowed to cure for some minimum time (24 hours for cement). The agglomerates can be evaluated in one of several ways to determine strength, including slump/percolation testing in columns (Pyper et al. 2015), dunk tests, and soak tests (Vethosodsakda et al. 2013).

Ore samples intended for column testing are typically crushed in jaw crushers to the size of interest; often near ROM, P_{80} 37 mm (1.5 in.), and P_{80} 12 mm (0.5 in.). These sizes typically represent ROM, secondary crushed, and tertiary crushed product. After passing a sample through the crusher, the product should be screened and oversize material returned to the crusher until the desired sized distribution is achieved.

For competent core, laboratory crushing often does not generate the amount of fines that blasting, mining, and field crushing do. In this case, the size distribution of the material to be tested should be adjusted to match *as-processed* size distributions to avoid a negative bias in the leach results caused by a lower degree of liberation. The product size distribution of a commercial cone crusher can be used as a target for PSD adjustment. Adjustment involves screening the entire composite at three of the coarser size fractions and comparing the fractions to the commercial product sizings. Splitting out and crushing a portion of the coarser fractions to finer sizes may be required to generate a PSD similar to the expected field operation.

Column testing at coarse crush sizes to represent ROM ore is limited to the size of the drill core available. PQ core (diameter 85 mm [3.3 in.]) is the most common of the larger core sizes used in exploration drilling, although core up to 300 mm (11.8 in.) can be obtained using specialty drill rigs.

Prior to column testing, splits are taken from the composite sample. One split is pulverized to less than 75 µm (200 mesh) and analyzed for head grade, multi-element analysis, and mineralogy. Mineralogy is often done with a combination of optical microscopy and scanning electron microscope techniques such as Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) or mineral liberation analysis.

Another split is screened into pertinent size fractions with each fraction pulverized and submitted for key metal assays. The results of this PSD with assays are later compared to the column residue sample PSD.

Copper head samples are typically further analyzed for acid-soluble copper and sulfide solubility using procedures such as the sequential copper leach procedure, QLT, or similar procedures modified for specific deposit characteristics.

Precious metal samples are typically analyzed for cyanide-soluble gold and for total precious metals by fire assay, as well as silver, organic carbon, carbonate, sulfide sulfur, sulfate sulfur, arsenic, antimony, mercury, base metals, and so forth. Larger pulverized or ground ore splits are generally employed in BRTs.

Two principal methods are used for preparation of column charges; if care is taken in sample preparation, either method should produce statistically reproducible results:

1. Samples are blended through statistically defensible techniques such as coning and quartering, then split through rotary or riffle splitters.
2. The entire sample can be screened into predetermined size fractions, then each size fraction is riffle split. Column charges are made up by recombining size fractions in appropriate percentages to rebuild representative samples.

If required, agglomeration of the column charge is typically performed in a cement mixer and done on a batch basis. Moisture must be added slowly until agglomerates are formed that are considered satisfactory or until the target moisture addition as per the agglomeration optimization test work is obtained. The quantity of moisture and reagents added must be recorded and included in the metallurgical balance of the test. Agglomeration of the sample will employ cement or lime addition (precious metals), acid addition (copper), or polymer binders (gold, copper, uranium, nickel laterites). Samples are then loaded into columns in a manner that reduces size segregation. Tapping the column walls during loading compacts the material to better simulate the consistency expected in field operations.

If possible, samples should be tested at the intended operational PSD and the operational lift height. To reduce wall effects and other preferential flow patterns, a rule of thumb is that column diameter should be roughly six times the largest ore particle diameter. A more or less standard minimum ore bed height is 1.8–2.0 m (~6 ft), but taller columns are more representative of field lift heights.

Column solution application practices vary between gold/silver and copper column leach testing. Typically for gold, solution is applied at or near the field application rate irrespective of column height. Leach testing is generally stopped when a solution-to-ore ratio of approximately 3 is reached; however, short columns (<3 m [9.8 ft]) often are run to much higher ratios, which then impact on scale-up assessments.

Copper leaching is more sensitive to ore diffusion and reaction kinetics; therefore, solution is generally applied at a ratio of column height to application rate and using a set cycle time. This results in solution being applied based on a solution volume-to-mass-of-ore ratio similar to gold testing, but within a set period. This has been shown to result in more representative estimates of acid consumption and extraction (Rood 2000).

Previous research has shown that small columns are generally well aerated, but occasionally are air starved. To avoid limitations in oxygen content, copper sulfide leach columns should be aerated at a flux similar to that intended for the field scale application. This is usually done using laboratory compressed air and controlled through flowmeters. Aeration rates are generally 100% of the air requirements necessary to achieve target extractions over the intended leach cycle time.

Columns can be irrigated on a continuous or intermittent basis using metering pumps. Pregnant solution should be collected on a regular basis (daily or on alternate days), weighed, and sampled. It is important that assays be carried out in a timely fashion to avoid changes in solution chemistry caused by oxidation, precipitation, evaporation, and so forth. Samples must be carefully measured for volume and other elements of interest. General analyses are as follows:

- Copper—copper, total iron, ferric iron, Eh, pH, and free acid
- Precious metals—gold, silver, (possibly copper and mercury), free cyanide, and pH

Often, the pregnant solution is passed through a metal recovery step (solvent extraction for copper or activated carbon for precious metals), then recycled after adjusting the solutions to the target leach conditions. This allows monitoring of the buildup of other species, which could affect downstream operations and ultimate process plant design.

Following completion of leaching, columns should be broken down and the tailings/residue assayed for grade and any other metal of interest as well as residual moisture content. A portion of the tailings should be submitted for a PSD with fraction assays to compare with the head sample. This can sometimes give an indication of expected extractions at coarser or finer crush sizes.

Metallurgical balance calculations will result in extraction curves based on the tailings assays and pregnant solution samples taken over the leach cycle. The extraction based on metal recovered in the pregnant solution treatment step can also be compared. Other data generated from each column test should include

- Days leaching,
- Solution-to-ore ratio of applied leach solution,
- Reagent consumptions (after allowing for reagents lost to samples and remaining in final solutions),
- Ore slump,
- Final ore bulk density,
- Head and tailings moisture content, and
- Percolation/permeability problems or other physical observations.

Column and bottle roll tests are often conducted in duplicate to provide a further level of comfort in leach performance. However, if the leaching behavior has previously been shown to be relatively consistent and if sample availability is limited, then random duplicates are often acceptable. If possible, column (and bottle roll) tests should be conducted using site water. This is especially important if project water quality is poor. A full water analysis and pH buffer curve are required to identify potential problems. A few operations employ seawater for processing due to unavailability of fresh water. These factors need to be taken into account when designing the column test program.

Scaling tendencies of makeup water and recirculating solutions are important for final design and during operations. Water treatment chemical suppliers often assist in assessing scaling tendencies of water and solution samples. Additional testing on physical aspects of the ore samples is required to assist in project design and cost estimating.

Field Trials

Full field trials of crushed ore at the proposed project stack height can be conducted as another option for evaluating heap leach potential and obtaining operating and cost data. Field trials were common in the early stages of the industry, including for uranium, copper, and gold, and most recently for nickel laterites. As experience was gained in extrapolating laboratory column test data to field operations, the prevalence of field trials has decreased.

For the most part, field trials are now deemed necessary only when there are significant unknowns in the scale-up process such as very high clay content, unusual leach behavior, or new process technology (Efthymiou et al. 1998). Financial institutions or company directors may insist on a field trial to reduce perceived project risk.

Run-of-Mine Ore Evaluations

As discussed, determination of crush size is normally conducted through one or more series of bottle roll or column tests at different crush sizes. However, when very coarse sizes show good leach behavior, it becomes difficult to verify expected field performance in bench-scale laboratory programs. Large-diameter whole core with minimal crushing (to generate some fines as per mining) can be employed in columns. Even so, the results still require extrapolation to a size distribution expected in field conditions—often with rock sizes of 1 m (3.3 ft) or larger. Bartlett (1998) presents a methodology for this type of extrapolation and discusses the risks involved while Bennett et al. (2003) discusses modeling of copper dump leaching from column leach data.

Otherwise, large columns or cribs can be set up with as-mined samples employed in a scaled-up version of a bench column test. Most commercial testing laboratories have facilities for large column tests or cribs to heights of 6 m (19.7 ft) or taller and crib dimensions up to 4 × 4 m (13 × 13 ft).

Another option for ROM ore evaluations is a full field trial where a very large sample is mined, dosed with reagent as needed, stacked, and leached. Field trials can range from a few thousand to 500,000 t (metric tons) (551,155.7 st [short tons]), with relevant facilities eventually incorporated into the full project design. However, the same drawbacks exist as for heap leach field trials, and even for large column or crib tests.

In several instances, heap leach operations have been set up based on a column test database of crushed ore, then once operations have begun, field testing of ROM ore is undertaken. Often, lower-grade ROM ore is placed as upper lifts on crushed ore heaps to save on capital for leach pads. See Gőkdere et al. (2015) for one gold mine's approach to ROM testing.

SCALE-UP TO FULL OPERATION

Scale-up to a full production operation is required when a successful column test program is translated into a final project design. For the scale-up process, taller columns (closer to full field lift height) provide a more reliable database. Column tests are generally considered an ideal leaching environment, so predictions of field extraction are based on final column test extractions but with some allowance (discounting) for field conditions that are seldom optimum or ideal.

Generally, final column extractions are discounted by 2%–10% for gold and copper ores and possibly by higher amounts for silver ores. The discounting is based on expected operational issues that may impact crush size or agglomerate quality, channeling within the heap, weather events, or other potential factors. One source of lost extraction is because of the difficulty in leaching side slopes effectively. Another is metal tied up in leach solutions in lower lift ores that may or may not be washed out over the course of the project life.

Another factor to consider when scaling up is the field leach time that will be available. Although the main advantage

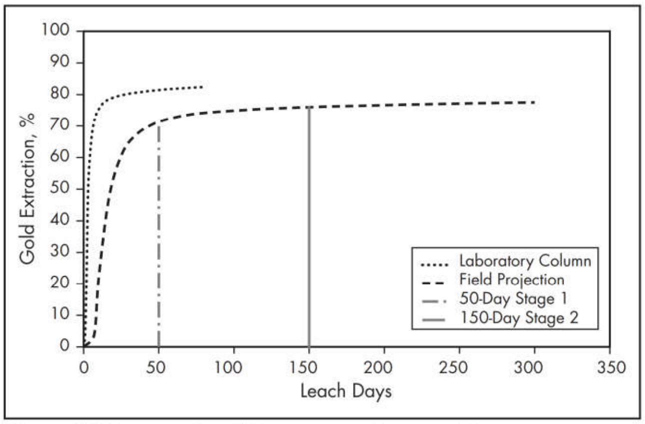


Figure 10 Extrapolated leach curve for a gold ore

of heap leaching over other process routes is time, leach pad and pumping design puts limits on the leach time available for ore in a given cell in a given lift. If leach time is limited compared to the scaled-up column time requirement, then further discounting may be required.

Typically, column extraction data used to develop production or field leach curves often take the shape of

$$F(t) = e^{-kt}$$

where
F(t) = metal extraction at time t
k = a fitting parameter constant
t = time

Other methods for predicting recovery from column data are described by Bartlett (1998). Bartlett uses the *shrinking core* model summed over multiple size fractions to allow for scale-up extraction predictions. The most common approach when larger (taller) column test data are available is based on the solution-to-ore ratio (sometimes called *flux*) that was required in the column to achieve a target extraction for a given leach time.

A typical scale-up situation is shown in Figure 10 where the laboratory extraction curve is shown along with the projected field leach curve including a 4% discount to the final laboratory extraction. Note where a 150-day leach cycle has been designated, which can be a single stage of leaching or a 50-day primary leach cycle (generating PLS) and a 100-day secondary leach cycle (generating ILS). When these time requirements are considered, another 2% discount is required from the final column recovery. It is possible that the discounted 2% of total gold will be extracted during leaching of upper lifts, but this not guaranteed and is thus considered upside potential when evaluating the economics of the project.

Another value to project for field operations is the bulk density of the stacked ores. Because of wall effects in leach columns, bulk density values are often lower in the columns than in actual heaps. This factor is employed in scaling of column test results as well as in crushing plant design and leach pad sizing.

When determining expected metal production from a heap or dump leach project, it is important to note that there will be losses in downstream operations that must be included in the final recovery values (as opposed to extraction values from the heap or dump).

LEVEL OF EVALUATION

As with any project evaluation, there are usually three stages prior to final design and construction of a heap or dump leach operation.

Initial Evaluations (Scoping Studies)

Testing can be limited to BRTs and possibly a few column tests.

Prefeasibility

Significantly more data are required involving IBRT and column tests on ore samples representing all the deposit lithologies. Additional tests are conducted to verify crush size and agglomeration requirements. For copper leaching, the leach regime (acid dosing, acid strength during leaching, aeration, bacteria, etc.) could encompass many column tests to assist in process design and confirm field requirements.

Final Feasibility Study and Final Design

The database must be completed to ensure appropriate ore treatment equipment selection, leach pad and pump sizing, recovery plant design, and other operational issues through decommissioning and closure. Confirmation testing is conducted, including reagent optimizations and additional geomechanical testing to verify permeability and heap stability at design lift heights and number of lifts.

Bench-scale or mini-pilot runs of solution treatment/metal recovery steps may be warranted (solvent extraction) employing solutions generated in column and bottle roll testing. Key column tests should include appropriate wash and draindown procedures at the end of the leach cycle to develop data for closure options. For cyanidation, water washing in batches with low-level cyanide speciation analyses will generate data for use in closure planning and submissions to appropriate regulatory agencies. Similarly, copper leach tests should include evaluations of residual solutions and their potential requirements for neutralization.

Production Models

Many models have been developed for predicting heap and dump leach performance, including several references in this chapter (Cathles and Apps 1975; Cathles and Schlitt 1980; Dixon and Hendrix 1993a, 1993b, 1993c; Keller et al. 2015; Marsden and Botz 2017; McBride et al. 2015; Roman et al. 1974) with each having additional references. Also refer to Chapter 2.5, "Modeling and Simulation."

Best practice for modeling extraction and production on an ongoing basis includes taking regular samples or monthly composites of leach ore for analysis and quality control (QC) leach testing and then trending extraction over time based on laboratory as well as production results. This historical data is then used to refine extraction formulas.

Whatever methodology is used in the leach production plan, it must be reviewed regularly and revised to match operational reality. Mines with historic production records and an extensive column leach database have an advantage.

Proper sample collection and evaluation are required for overall performance assessment and reconciliation of the ore

Table 1 Heap and dump key production indicators

• Head grade	• Solution-to-ore ratio–cumulative, m^3/t
• Tonnage stacked	• Lixiviant concentration, on
• Ore blend	• Lixiviant concentration, off
• Crush size, P_{100} and P_{80}	• Leach solution pH, on
• Moisture content	• Leach solution pH, off
• Agglomeration reagents	• Pregnant leach solution (PLS) grade
• Agglomeration water	• PLS treated
• Agglomerate quality	• Metal recovered
• New area under leach	• Efficiency of recovery
• Total area under leach	• Total metal in inventory
• Application rate, $L/h/m^2$	• Recoverable metal in inventory

body with the block/mine model (Chieregati and Pitard 2009). For ROM dump leaching, blasthole or grade control samples usually constitute the only source of assay data for ore to the dump. However, solution analyses must still be conducted.

Production Monitoring

Many operations now have sophisticated data collection and control systems. But with or without them, overall heap or dump leach production monitoring involves tracking a significant amount of data. These range from start and end dates for leach cells to rainfall to reagent additions to month-end metal inventories (heaps, ponds, recovery system).

The metal production model must be updated monthly to verify assumptions for short- to mid-term forecasting. QC bottle roll and column test results on actual stacked ore composite samples are critical to update the model results and projections.

Heap and dump surveys are required as part of the overall reconciliation with mine data. It is often the case that ore tonnage delivered to the ROM stockpile does not match weightometer readouts of ore processed through the crushing plant. In this case, ore bulk density based on crusher tonnage and heap survey volumes can be checked against mine department volumes and assumed swell factors.

Heap and dump surveys are also critical for monitoring slump. Excessive slump will lead to extraction/production losses through compression and elimination of void spaces in the heap. A 10% or greater slump is the value above which a fall-off in extraction will become noticeable (Pyper et al. 2015). Table 1 shows some key production indicators (KPIs) for heap and dump operations. There will be other KPIs for specific aspects of individual projects and depending on the metal(s) being leached.

DECOMMISSIONING

Decommissioning of spent heap and dump leaching operations cannot be adequately addressed in this chapter. Indeed, the approach to final closure of a heap or dump is highly site specific with several options available. The general consensus is that decommissioning is much more involved and time consuming than had been allowed for by many companies.

The steps include winding down of operations after final stacking of ore, efforts to increase extraction from older heaps and dumps, the appropriate rinsing approach, draindown issues, and final closure, including recontouring and capping.

Winding Down Operations

Even in well-operated heaps, there could be a recoverable 3%–10% metal left as inventory after completion of leaching caused by compaction, fines migration, heap settlement, clay zones, solution management, and zones with adverse chemistry. Attempts to recover these additional values can involve re-ripping the surface, *turning* (or re-mining) all or part of a lift with an excavator, or even drilling and blasting to generate new flow paths. These are followed by continuous or intermittent leaching. Targeted releaching is perhaps the most sophisticated approach to maximizing metal extraction from older heaps (Seal 2007, 2011, 2015).

Closure of Precious Metals Heaps

Because heap leaching of gold and silver ore is relatively young (approximately 50 years), closure of precious metals heaps was not considered a major issue until a sufficient number of heaps had been operated for many years and closure activities were initiated—beginning in the late 1980s. The procedures for closure of heaps are dependent on the climate of the area, particularly the rainfall, but also on the quality of the off-flow draining from the heaps. In very wet areas, heap leach operations will be closed differently than in arid regions. Ultimately, drainage from heaps in wet areas will likely be managed until the drainage water quality meets discharge standards (Parshley et al. 2012).

How long this takes depends on the amount of rainfall and the geochemistry of the heap, as well as the regulatory issues in the specific state or country. Ultimately, the industry and consultants have realized that fresh water rinsing would simply *not* allow a walk-away solution. In almost every case, the quality of the released water will be sufficiently poor that some sort of management will be required. And, particularly in arid regions, allowing meteoric water to rinse the heaps to remove the salts will require a time frame of several years to decades (Decker and Tyler 1999).

In arid environments, closure procedures generally involve store-and-release caps in which heaps are covered with sufficient growth medium to capture the water during the periods of precipitation, and allow vegetation to absorb the water for plant growth during the drier periods. The goals are to prevent or minimize water from penetrating into the closed heap and to create a diverse plant community that can support productive post-mine land uses.

Closure Chemistry of Cyanide Heaps and Dumps

Following active cyanide leaching of a heap, addition of cyanide is discontinued, and the solution is continuously recirculated to capture remaining precious metals. This begins the process of reducing the volume of the recirculating fluids. In arid regions, this is most commonly accomplished by sprinklers or misters to evaporate water, a process that can take months to years.

The chemistry of cyanide heaps must address the following issues:

- Cyanide removal (Johnson 2015)
- Salt accumulation
- Mercury releases (Flynn and Haslam 1995)
- Arsenic and other oxyanions (Miller et al. 1999)

Management of Closed Heaps: To Rinse or Not to Rinse

The initial approach to heap closure was to recirculate solution in a heap until weak acid dissociable (WAD) cyanide was down to 0.2 mg/L, followed by rinsing with fresh water. As observed in column studies (Miller et al. 1999), the mobile constituents (e.g., chloride and nitrate) are largely removed in less than one pore volume of water passing through the heap material under unsaturated flow conditions. Sulfate and selenium are 90% reduced in three to four pore volumes, but as the mobile constituents and acidity are removed, calcite retained in the heap material raises the pH to 8.3–8.5, and arsenic and vanadium concentrations in the column effluent (after six pore volumes) increase to greater than the applicable drinking water standard. Thus, management of the rinsed heap effluent will still be required, even if most of the salts have been removed. The rinsed heaps will likely still be discharging poor-quality water that will need to be managed, probably by evaporative processes. For heap closures in arid climates, rinsing does not solve the contaminant issue. Plus, rinsing is costly and consumes water.

The option that is now more commonly accepted (Parshley et al. 2012) is to establish a store-and-release cap for a heap. Complete elimination of drainage from a heap is unlikely and depends on the amount of rainfall as well as the closure methods used. Regulatory agencies in Nevada (United States), particularly the Nevada Division of Environmental Protection (NDEP), are increasingly convinced that closure of heaps will require caps that can eliminate (or substantially reduce) the amount of water allowed to penetrate the heaps each year. NDEP also requires evaporation basins that capture drainage from the heaps during the 100- to 500-year events. But nobody can predict how climate change will affect precipitation patterns during the upcoming decades into the future.

Heaps are most often composed of oxidized ore, and acidification is not common. However, when sufficient sulfidic rock is present in the spent ore to generate acids, the problems with closure can be substantially increased. Acidic water draining from the site will need to be managed, primarily by neutralization and evaporation.

In areas where meteoric water is substantial, using store-and-release caps may not be successful, and a combination of processes may be required to limit the amount of water that will be discharged. But ultimately, discharge of detoxified solution to surface water may be one of few options. The mobile constituents will be discharged relatively soon after closure (years) while the less mobile constituents will be discharged over a longer period. Permitting a heap in regions that receive large amounts of meteoric water should recognize that closure of the heaps may be problematic.

Closure of Acid Heaps

Although experience with closure of precious metals heaps has established methods for closure, much less experience is available in the literature on closure of copper or uranium heaps where sulfuric acid is employed as lixiviant (Borden et al. 2006; Smith 2002). Although heap leaching of copper ores has increased during the past 40 years because of improved recovery technology, closure of these heaps is generally more complicated than gold heaps.

First, the heaps are often much larger, owing to large copper ore bodies, where decades of acidic leaching has been conducted. Sulfuric acid requires neutralization with lime or some other alkaline material, which is generally unfeasible for large heaps. Concentrations of total contaminants being released from a closed copper heap can be large. In one case, the total dissolved solids in off-flow solution was 90,000 mg/L, with a pH of 2.9 (Borden et al. 2006).

Climate is perhaps the most critical factor for closing heaps. In extremely dry regions of the Atacama Desert in northern Chile, rainfall is often nonexistent. Consequently, the challenges for closing copper heaps are much less severe as the heaps will ultimately drain, and water from rainfall will be minor. In other parts of the world where higher levels of precipitation exist, however, closure will be a major challenge. Even in relatively arid areas, meteoric water is expected to result in long-term drainage when the heap is not properly closed (Smith 2002). Closure of copper heaps will require additional discussions and research.

Heap Capping and Covers

As discussed in previous sections, heap and dump capping and covers are key elements in successful closure. Heap capping has three main goals:

1. Reduce the potential for erosion.
2. Mitigate seepage from the heap into the natural groundwater.
3. Mitigate and/or reduce runoff and rainfall infiltration.

The general approach to heap and dump rehabilitation is broken down as follows:

1. Push down the side slopes to achieve a target overall angle of repose of 18–21 degrees, depending on regional environmental guidelines. Some jurisdictions may require "geomorphic reclamation" where the dumps are contoured to mimic the surrounding terrain (Stebbins 2015).
2. Place a containment berm around the entire leach pad/pond footprint to prevent ingress of surface runoff and release of potentially contaminated solutions.
3. Place a multilayered store-and-release cover on the top surface of the heap. These layers can consist of waste rock fill, sand, compacted clay, GCL, random soils, topsoil, and vegetation.
4. Place a containment bund around the top surface of the heap to reduce the potential for erosion of side slopes from surface runoff.
5. Place a thick cover of armoring rock and/or topsoil with vegetation on the side slopes.

A review of cover options is presented in Rykaart and Caldwell (2006), and more recent advances in acid rock drainage control are discussed in INAP's *Global Acid Rock Drainage Guide* (2009).

New Technology for Drying Heaps

Preventing meteoric water from infiltrating the heap is an established method for reducing drainage volume. Alternatively, additional methods for removal of water from the heap by evaporation can also potentially be utilized. Seal and Kiley (2015) have proposed such a system for using forced air to evaporate water from the interior of heaps. This technology has been demonstrated under laboratory conditions using actual heap material).

COSTS

Capital and operating costs for heap or dump leach operations can vary considerably depending on location, topography, ore type, downstream process requirements, project size, infrastructure requirements, and several other factors.

For a comprehensive analysis of heap leach costs for gold deposits, InfoMine has recently released a 200-page *Gold Heap Leach Cost Estimating Guide* (2016). For further accuracy, it would be necessary to prepare a preliminary feasibility study. Where the project economics are complex, it is often (but not always) necessary to follow this up with a full feasibility study.

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