Precious Metal Heap Leach Design and Practice

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ABSTRACT
Heap leaching of gold and silver ores is conducted at approximately 120 mines worldwide. Heap leaching is one of several alternative process methods for treating precious metal ores, and is selected primarily to take advantage of its low capital cost relative to other methods. Thirty-seven different heap leach operations with a total production of 198 tonnes of gold per year (6,150,000 ounces/yr.) were surveyed to determine operating practice. These operations together produce 7.4% of the world's gold. When mines not surveyed are taken into account, it is likely that heap leaching produces 12% of the world's gold. Heap leaching for silver is conducted using the same principles and operating practices as for gold, but heap leach operations produce only a small fraction of world silver production.

INTRODUCTION
Heap leaching had become a fairly sophisticated practice at least 500 years ago. Georgius Agricola, in his book De Re Metallica (publ. 1557) illustrates a heap leach with a 40-day leach cycle (Figure 1), which could pass in many ways for a modern heap leach. The Agricola heap leach recovered aluminum (actually alum) for use in the cloth dying industry. Copper heap and dump leaches in southern Spain were common by about 1700. Gold and silver heap leaching began with the first Cortez heap leach in 1969. While many projects have come and gone, Cortez is still going - their new 63,000 tonne/day South Area leach is scheduled to start up in 2002.

The largest U.S. precious metal heap leach is the Round Mountain, Nevada, operation with over 150,000 tonnes/day of ore going to crushed or run-of-mine heaps, at an average grade of 0.55 grams gold/tonne [This chapter follows the North American convention of "ton" for short ton and "tonne" for metric ton]. Worldwide, Newmont's Yanacocha, Peru, operation holds the record, with a 2002 target of nearly 370,000 tonnes/day, at an average total reserve grade of 0.87 grams gold per tonne. On the other end of the scale, some very high grade ores - up to 15 grams per tonne (0.5 oz/ton) - are being successfully processed at rates of several hundred tonnes/day (Sterling, Nevada; Hassai, Sudan; Ity, Ivory Coast). A cursory worldwide summary in late 2001 was able to identify 78 active precious metal heap leaches worldwide, of which 34 were in the U.S. (22 in Nevada). The survey no doubt missed many operations, so the worldwide total is certainly over 100. To provide a basis for this chapter, technical and/or cost data were gathered from 37 of these operations. Because many operations impose restrictions on the release of detailed data, composite results are presented.

Nevada was the "birthplace" of modern gold heap leaching in the late 1960's, and is only now giving up its dominance of this technology. Other very large gold districts - notably the pre-cambrian shield areas of Canada, Australia and South Africa - show relatively few heap leaches. There are several reasons for this geographic concentration, but the primary reason is that Nevada gold deposits tend to have been created by low-energy geologic processes - near surface hot

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springs and moderate depth, hydro-thermal systems that deposited low grade gold in permeable rocks. Besides aiding gold deposition, the permeable nature of the rocks allowed uniform and deep oxidation that liberated the gold from its sulfide and carbonaceous host minerals. Shield deposits have generally had a more complicated history, which has resulted in coarse gold contained in poorly-permeable rocks. Often these ores can be successfully heap leached only after weathering has completely destroyed the rock matrix.

Figure 1. "The rocks are . . piled in . . heaps fifty feet long, eight feet wide and four feet high, which are sprinkled for forty days with water. The rocks begin to fall to pieces like slaked lime, and there originates a . . new material". Drawing and text from De Re Metallica, Herbert Hoover translation, published by Dover Publications, Inc.

WHAT IS HEAP LEACHING?

To those of us in the gold industry, the question "What is Heap Leaching?" seems to have an obvious answer. In the 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 2 is an aerial photograph showing the typical elements of a precious metals heap leach operation - open pit mine, a heap of crushed ore stacked on a plastic pad, ponds, a solution process facility for recovering gold and silver from the pregnant solution, and an office facility. 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 non-trivial expenditure of capital, and a selection of operating methods that trade off cost versus marginal recovery. Success is measured by the degree to which target levels and rates of recovery

Figure 2 Heap leach installation at Mineral Ridge, Nevada. The open pit mine is shown on the left. On the right is a two million ton heap of crushed, conveyor-stacked ore placed on a plastic-lined leach pad. Pregnant and barren solution storage ponds are located downslope from the heap. Buildings include process plant, laboratory, maintenance shop and administration offices. Photo courtesy of Tom Nimsic, American Au/Ag Associates.

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 achieved with any level of net positive cash flow.

The bibliography of precious metals heap leaching is quite extensive, and because of time limitations a very limited bibliography has been compiled for this chapter. However, the following publications are good places to start a literature search:

- "Global Exploitation of Heap Leachable Gold Deposits", by Hausen, Petruk and Hagni, February, 1997
- "The Chemistry of Gold Extraction" by Marsden and House, 1992
- "World Gold '91", Second AusIMM-SME Joint Conference, Cairns, Australia, 1991
- "Introduction to Evaluation, Design and Operation of Precious Metal Heap Leaching Operations", by Van Zyl, Hutchison and Kiel, 1988.

Special recognition and thanks should be given to Hans von Michaelis of Randol International, Denver. Between 1981 and April 2000 Randol organized four major symposia followed by four published studies of the gold industry, and several minor meetings with their own proceedings. The combined Randol literature occupies nearly 40 volumes covering six feet of shelf space. Most modern heap leach operations are referenced.

WHY SELECT HEAP LEACHING AS THE PROCESSING METHOD?

Gold and silver can be recovered from their ores by a variety of methods, including gravity concentration, flotation, and agitated tank leaching. Methods similar to heap leaching can be employed: dump leaching and vat leaching (vat leaching is the treatment of sand or crushed ore in bedded vats with rapid solution percolation).

Typically, heap leaching is chosen for basic financial reasons - for a given situation, it represents the best return on investment. For small operations or operations in politically unstable areas, it may be chosen because it represents a more manageable level of capital investment. Some interesting examples that illustrate this issue of choice are presented below.

Capital Risk

Several years ago, the author's company was advising on a project in which the ore reserve was a few million tonnes at a grade of 7 grams of gold per tonne (0.22 oz/ton). Heap leach recovery was about 80%, well below the 92% that could be achieved in an agitated leach plant. Financial considerations strongly favored milling, and the owner was financially strong. However, the operation was located in an undeveloped country with unstable politics and socialist leanings. The owner concluded that he might lose control of a high-capital investment, whereas he could maintain control of a heap leach with an implied promise of a future larger capital investment. The operation has been running successfully and very profitably.

Lack of Sufficient Reserves

The Sterling Mine in Beatty, Nevada (Cathedral Gold Corporation) began life as an underground mine, with a reserve of 100,000 tons of ore at a grade of 11 grams gold/tonne (0.35 oz/ton). Over a fifteen year period, it mined and processed nearly one million tons, but never had enough ore reserves to justify a conventional mill. Fortunately, the Sterling ore achieves excellent heap leach recovery - the original heaps reached 90% from ore crushed to 100 mm.

Equal or Better Percent Recovery

Comsur's Comco silver heap leach at Potosi, Bolivia, showed the same recovery in both a heap and an agitated leach plant. However, the silver ore leached very slowly and residence time of up to 4 days was needed in an agitated leach plant. Although the heap leach took several months to achieve the same recovery, the economics favored the heap.

At the joint AIME/AusIMM Symposium "World Gold '91", T. Peter Philip of Newmont presented a paper "To Mill or to Leach?" in which he evaluated the decision of Newmont to build the Carlin No. 3 mill. He concluded that the mill recovery was over-estimated and the heap leach recovery underestimated, and that the decision to go with milling may have been incorrect.

Differential Recovery Is Not Sufficient To Justify Added Investment

A recent review (Kappes, 1998) concluded that for a "typical" Nevada-type ore body with ore grade of 3.0 grams gold/tonne (0.088 oz/ton), the mill recovery would have to be 21% higher than the heap leach recovery to achieve the same return on investment - and this is very seldom the case.

Of the 37 operations surveyed for this chapter, four have a head grade below 0.65 grams gold per tonne and half are between 0.65 and 1.50 grams per tonne. At these gold grades, it is usually impossible to justify the investment in a conventional agitated leaching plant.

Capital Is Very Difficult Or Expensive To Raise

Heap leaching has often provided the route for a small company to grow into a large company. A good example is Glamis Gold Corporation, which has gone from total assets of $12 million in 1984 to $112 million in 2001, based largely on its low grade heap leach projects at Picacho and Randsburg, California.

At the time this is being written in early 2002, the precious metals mining industry is experiencing a severe capital shortage and a consolidation of producers into a few large corporations. This will open up an opportunity for the creation of a new generation of junior mining companies to exploit smaller deposits, and heap leaching will play a key role in this process.

TYPE OF ORE

Heap leach recovery is very dependent on the type of ore being processed. Some typical examples are discussed below.

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. Ores are typically coarse-crushed (75mm) but may show recovery of 70% or better at run-of-mine sizes. The largest of the northern Nevada heap leaches (Carlin, Goldstrike, Twin Creeks) treat this type of ore. Unoxidized ore contains gold locked in sulfides, and also contains organic (carbonaceous) components, which absorb the gold from solution. This ore shows heap leach recovery of only 10 to 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 minesite. Crushing is usually done in conventional systems (jaw and cone crushers) and ores are truck stacked.

Low Sulfide Acid Volcanics Or Intrusives

Typical operations treating this type of ore are Round Mountain, Nevada, and Wharf Mine, South Dakota. Original sulfide content is typically 2 to 3% pyrite, and the gold is often enclosed in the pyrite. Oxidized ores yield 65 to 85% recovery but may have to be crushed to below 12 mm (1/2 inch). Usually the tradeoff between crush size and percent recovery is a significant factor in process design. Unoxidized ores yield 45 to 55% gold recovery and nearly always need crushing. At Round Mountain, Nevada, approximately 150,000 tons per day of low grade oxide ore is treated in truck-stacked run-of-mine heaps, 30,000 tons per day of high grade oxide ore is treated in crushed (12mm), conveyor-stacked heaps, and 12,000 tons per day of unoxidized ore is treated in a processing plant (gravity separation followed by leaching in stirred tanks). Crushing is done using jaw and cone crushers; fine 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 75mm often does not increase heap leach recovery. The Filon Sur orebody at Tharsis, Spain (Lion Mining Company) and the Hassai Mine, Sudan (Ariab Mining Company) are successful examples of heap leaches on this type of ore. Because the ore is fine and soft, the ore is agglomerated using cement (Hassai uses 8 kg cement/tonne), and stacking of the heaps is done using conveyor transport systems.

Saprolites / Laterites

Volcanic- and intrusive-hosted orebodies 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 to 95% gold recovery in lab tests, 85% or greater in field production heaps. Ores are processed at run-of-mine size (which is often 50% minus 10 mesh) or with light crushing. Ores must be agglomerated, and may require up to 40 kg of cement per tonne to make stable permeable agglomerates. Many of the West African and

Central American heap leaches process this type of ore. Good examples are Ity in the Ivory Coast, and Cerro Mojon (La Libertad) in Nicaragua. When crushing is required, one or two stages of toothed roll crushers (Stammler-type feeder-breaker or MMD 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, as well as in some volcanic-hosted deposits, clay deposition or clay alteration occurred along with gold deposition. The Buckhorn Mine, Nevada (Cominco, now closed) and the Barney's Canyon Mine, Utah (Kennecott) are good examples. 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.

Barney's Canyon employs belt agglomeration (mixing and consolidation of fines as it drops from conveyor belts) followed by conveyor stacking. The new La Quinua operation at Yanacocha 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, 5% silver to 99% silver, 1% gold. Silver leaches and behaves chemically the same as gold, although usually the percent silver recovery is significantly less than that of gold. Examples of nearly pure silver heap leaches are Coeur Rochester and Candelaria in Nevada, and Comco in Bolivia.

CLIMATE EXTREMES

The ideal heap leach location is a temperate semi-arid desert location such as the western U.S. However heap leaching has been successfully applied in a variety of climates:

- Illinois Creek, Alaska, and Brewery Creek, Yukon are located near the Arctic Circle and experience temperatures of minus 30^{o}C for several months per year.
- Several heap leaches are located in the high Andes of South America (Comco at Potosi, Bolivia; Yanacocha and Pierina, Peru; Refugio, Chile) at altitudes above 4000 meters (13,000 ft). Although oxygen availability at these altitudes is only 60% of that at sea level, gold heap leaching proceeds at rates similar to that at sea level (oxygen is required for the process, but is not usually rate-limiting in a heap leach operation).
- At another extreme, Hassai, Sudan, is in the dry eastern Sahara fringes. This operation experiences normal daytime temperatures that routinely exceed 50^{o}C in the summer, with annual rainfall of less than 20mm. One of the advantages of heap leaching over conventional cyanide leach plants and gravity recovery plants, is that heap leaching consumes very little water. With good water management practices, water consumption can be less than 0.3 tonnes water per tonne of ore.
- In tropical wet climates, rainfall of 2.5 meters per year can add over 5 tonnes of water to the leach system for each tonne of ore stacked. As discussed in a later section, this amount of water can also be handled with good water management practices.

CHEMISTRY OF GOLD/SILVER HEAP LEACHING

The chemistry of leaching gold and silver from their ores is essentially the same for both metals. A dilute alkaline solution of sodium cyanide 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 to 11. Below a pH of 9.5, cyanide consumption is high. Above a pH of 11, metal recovery decreases.

Many heap leachable ores contain both gold and silver. Of the 28 mines that reported bullion assays, five produce a doré (impure gold-silver bullion) bar that is greater than 70% silver. Another five produce a bullion greater than 30% silver. Only five produce a bullion with less than 5% silver. Deposits in western Africa and Australia tend to be very low in silver, while those in Nevada 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 the metal, whereas silver may be present in the ore in many different chemical forms some of which are not cyanide-soluble. Reported heap leach recoveries (32 operations) averaged 71% gold, and ranged from 49% to 90%. Reporting run-of-mine heap leaches averaged 63%. Typical recovery for silver is 45-60%, although when silver is a minor constituent, its recovery may be only 15-25%.

The level of cyanide in the heap onflow solution ranges from 100 to 600 ppm NaCN, and averages 240 ppm for the 28 operations reporting. Forty-five percent of the operations reported cyanide strength below 200 ppm, 25% were above 300 ppm. Heap discharge solution (pregnant solution) averages 110 ppm.

Cyanide consumption, via complexation, volatilization, natural oxidation or oxidation by ore components, typically ranges from 0.1 to 1.0 kg per tonne of ore. Price of sodium cyanide is currently at a historical low of $1.00 per kg. Cement and/or lime consumption ranges from 0.5 to 40 kg per tonne of ore. Several operations use cement for alkalinity control (instead of lime) as well as for agglomeration. The price of cement or lime is $60 to $100 per tonne, $160 delivered to remote African locations.

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. A good discussions of the process chemistry can be found in "The Chemistry of Gold Extraction" by Marsden and House, Ellis Horwood Publishers, 1992.

LABORATORY TESTING & CONTROL

As with any processing method, it is very important to base the design on the results of a comprehensive program of laboratory testing. During the production operation, laboratory tests including column leach tests should be continued on a regular basis, since the initial ore samples are seldom representative of the entire orebody. For a heap leach, the key parameters that are defined in the laboratory are crush size, heap stability, permeability versus heap height, cyanide strength and consumption, the need for agglomeration and the amount of agglomerating agent (usually Portland cement) required, leach time, and percent recovery. Derivative parameters such as the height of individual lifts and the method of stacking are also determined.

Heap leaching has inherent risks that can be largely eliminated if the operating practices follow the results of initial and on-going laboratory testing. The risks result from the nature of the operation. The results of the process are usually not known for several weeks or 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 operating practices, for instance by not crushing finely enough, or by not agglomerating or stacking properly, can result in cash flow problems 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. For a small operation processing less than 5,000 tonnes of ore per day, staffing is 2-3 technicians for sample preparation and assaying and one metallurgist to conduct process tests. Large operations may have a laboratory staff of ten to fifteen people.

HEAP PERMEABILITY & 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:

- coarse channels, which allow direct short-circuiting of solution from top to bottom
- highly permeable zones, in which solution is efficient at contacting the rock and washing the gold downward in "plug flow"
- zones of low to zero permeability where high grade solution or unleached ore may be trapped.

Efficiency Of Solution Displacement

If the heap were "ideal" - 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 gold/silver content) requires that 0.8 tonnes of solution must be applied to each tonne of ore. Typical practice is to apply 1.3 tonnes of solution per tonne of ore during a 70-day primary leach cycle. This suggests two things: (a) most heap leach operations are able to maintain reasonably good permeability characteristics, yielding at least 50% wash efficiency; and (b) a high percentage of the gold is solubilized early in the 70-day leach cycle.

Drainage Base

A drainage base of crushed rock and embedded perforated pipes is 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 ore column, and then enter a solution removal system with zero hydraulic head. If the drainage base cannot take the entire flow then 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 meters in an upslope direction. All of the onflow solution in a strip one meter wide by 500 meters must flow out at the downslope edge of the heap through the drainage base, which is typically 0.65 meters thick. The design 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%. A similar effect has been seen but not quantified at gold heap leach operations.

Recovery Delay In Multiple Lift 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 gold 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 120 meters high, with about ten lifts of ore. Hard ore, crushed or run-of-mine, 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 meters; some agglomerated ores perform satisfactorily to 100 meters. 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). Of 22 operations reporting, 18 indicated that they see a delay in time of average recovery, which ranges from 3 to 30 days per lift. The most common figure was 7 days/lift. This cash flow delay must be allowed for. Also, this number implies that for each extra lift, the capacity of the process plant should be increased in response to the decrease in gold content of pregnant solution.

Intermediate Liners

If impermeability of lower lifts becomes a serious problem, it is possible to install intermediate liners. Four of the surveyed operations reported that they install plastic intermediate liners on a regular basis. One operation reported that it regularly installs a clay intermediate liner. There are two problems with installing an intermediate liner: (a) the heap below the liner is compressed as the upper lift is placed, resulting in differential settlement and tearing of the liner; and (b) the ore below the liner cannot be washed with water, which is sometimes required as a part of final heap closure.

SOLUTION APPLICATION RATE AND LEACH TIME

With regard to sprinkling rate, the timing of gold recovery is a function of five factors:

- the rate at which the gold dissolves. Coarse gold particles dissolve very slowly, and may not fully dissolve for several months in a heap leach environment.
- the percentage of gold that exists as free or exposed particles
- the rate of diffusion of the cyanide solution into rock fractures, and of gold cyanide back out of the rock fractures. Where the gold occurs 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 destroy cyanide and alkalinity or which consume oxygen
- the rate of washing of gold off of the rock surfaces and out of the lift of ore under leach. This is a complex issue, which depends on the overall permeability of the lift and the local permeability variations due to segregation and compaction as the lift is being constructed.

The above 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: Of 19 operations reporting, application rates for crushed-ore heaps ranged from 7 to 20 l/hr/sq. m (0.003 to 0.009 gpm/sq. ft) with an average of 11 l/hr/sq. m (0.048 gpm/sq. ft). Only three applied solution above 10 l/hr/sq. m (0.0044 gpm/sq. ft), and only four were below 8 l/hr/sq. m. (0.035 gpm/sq. ft). For 17 run-of-mine heaps, the average application rate was 8.3 l/hr/sq. m (0.037 gpm/sq. ft), with only two operations above 10 l/hr/sq. m (0.044 gpm/sq. ft).

Laboratory columns always respond much faster than field heaps, for two reasons: the ore is placed in the lab column much more uniformly so that percolation is more effective; and the solution-to-ore ratio (tonnes of solution per tonne of ore in a given time frame) is generally higher in lab columns than in field heaps. 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.

For the 32 operations reporting, average single lift height was 8.9 meters (yielding 14.2 tonnes of ore per sq. m of top surface) and average irrigation time was 70 days during the primary leach cycle. This yields a specific solution application rate of 1.30 tonnes solution per tonne of ore. Operations with low cycle times tended to have higher application rates, suggesting that the ratio of 1 to 1.5 tonnes of solution per tonne of ore is a universal target.

For ores with very slow leaching characteristics, an intermediate pond and a recycle stream may be added to the circuit, so that each tonne of ore sees two tonnes of leach solution during an extended leach period. The process plant treats only the final pregnant stream - one tonne of solution per tonne of ore. Of 36 operations reporting, 16 had only one leach cycle, 16 had two cycles, and four had three cycles.

The use of multiple cycles is good operating practice for single-lift heaps of high grade ore. However, for multi-lift heaps this is not the case. Heap modeling indicates that once the heap attains a height of three lifts, the intermediate solution contains almost as much gold as the pregnant solution. Recycling results in a significant build-up of dissolved gold within the heap, causing a slight overall recovery loss and a cash flow delay. For multi-lift 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.

Some successful single-lift heaps achieve a high percentage recovery in the first leach period, but continue the leach for much longer. Sterling, with very high grade ore, leached the same ore for 18 years. The initial Cortez heaps were leached intermittently for ten years. Cost to intermittently leach old heaps may be as low as $0.10 per tonne per month.

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 agitated, heap leaching is not a very energy-intensive process. Once a heap is built, one of the most significant variables, which the operator can employ to solve design or production problems, is leach time. Successful projects employing on-off (reusable) leach pads have been undertaken, but this is a risky practice. Some operations (such as Round Mountain, Nevada) utilized on-off pads to achieve rapid first-stage recovery, then transfer the ore to long term heaps to complete the process.

DESIGN FOR AMBIENT WEATHER CONDITIONS

Design For High Ambient Temperature

In regard to ambient temperature, high temperature is not a direct problem. In very hot desert areas where drip irrigation is used, sunlight will significantly heat the solution. Even then, because of the effect of cool night time temperatures, it is unusual to see heap effluent solution temperatures above 15^{o}C. Mesquite at one point covered the ponds to prevent evaporation, and the resulting recirculating solution was above 30^{o}C. Hot leach solutions dissolve less oxygen than cold solutions and this could affect the rate of gold recovery in oxygen-starved heaps. However, usually there is sufficient oxygen present, and the higher overall activity due to the higher temperature more than offsets the oxygen effect. No operating heap leaches have reported a direct problem due to high temperature of the rock or the leach solution.

Design For Low Ambient Temperature

Low temperature can be a problem. Many Nevada heap leaches report a significant recovery decrease in winter, which is offset the following summer. When a cold weather project is anticipated, column tests should be run under cold conditions. There are several reasons for a reduction in recovery rate with lower temperatures:

- Rate of reaction is slowed as solution tempeature approaches freezing. Comparative laboratory column tests show that recovery rate drops significantly when the heap temperature drops below 5^{o}C. Solution viscosity increases significantly as temperature drops. This affects both the heap and the process plant.

- Solution flowing slowly through the normally unsaturated heaps flows via the meniscus on the surface of particles, and the thickness of this meniscus is a direct function of viscosity. Thus, cold heaps tie up more process solution (and more gold inventory) than warm heaps. In carbon columns, the rate of fluidization can be significantly affected. PICA USA Inc. (one of several activated carbon suppliers) has generated a graph of solution temperature versus percent fluidization, which is shown as Figure 3. As the graph shows, bed expansion of carbon can increase from 15% to 33% as the solution temperature decreases from 20°C to 5°C. This same viscosity effect will alter the ability of the solution to flow through the heaps.

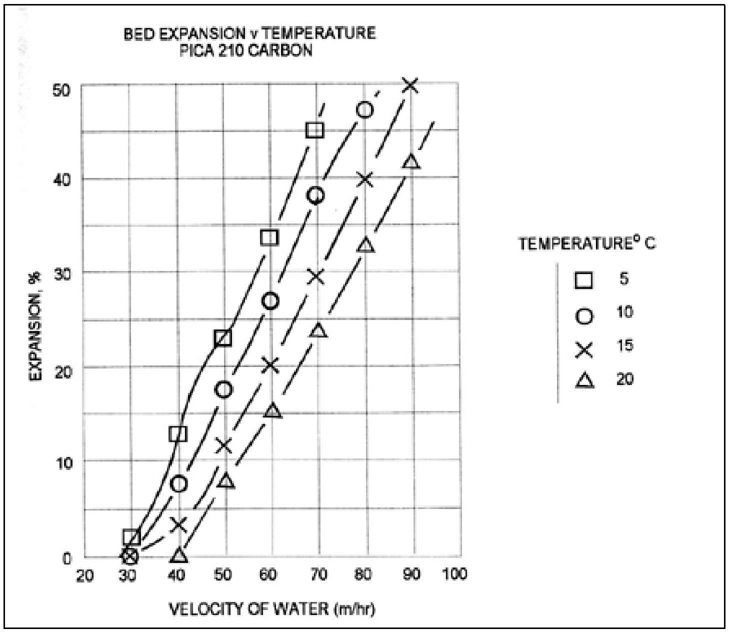

Figure 3 Effect of Temperature on Bed Expansion of Activated Carbon

- Solution surface tension drops, although not as fast as viscosity. Surface tension can affect the flow of solution through the heaps, and also it affects the ability of the solution to penetrate tight fractures within the rock. Table 1 shows the effect of temperature on the viscosity and surface tension of water.
- In very cold climates, it is possible to create a frozen wedge of solution within the heap. This occurred at Summitville, Colorado. For this reason, Brewery Creek (Yukon) stacks ore only in the summer, although they leach all year.

Temperature	Surface Tension, dynes/cm	Viscosity, centipoises
0°C	76	1.79
5°C	75	1.52
10°C	74	1.31
20°C	73	1.00
40°C	70	0.66

Table 1 Surface Tension and Viscosity as a Function of Temperature

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 requirements.

Evaporation of water, regardless of its mechanism, requires a heat input of 580 calories per gram (8300 BTU/U.S. gallon) 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.

Average 24-hr incident solar radiation on a flat horizontal surface ranges from 12,000 BTU per sq. m per day (central U.S.) to about 30,000 BTU (equatorial desert), which could theoretically evaporate 5 to 12 liters of solution per day. With a typical heap application rate of 10 l/sq. m /hr, incident solar radiation could account for an evaporation rate of 2 to 5% of applied solution when using sprinklers. Evaporation would be somewhat less when using drip irrigation (1 to 4%) because some of the solar energy is re-radiated from dry areas on top of the heap. This same heat input would result in pond evaporation of 5 to 13 mm per day.

Use of sprinklers rather than drips may result in the loss of up to 30% of solution pumped. This is because the sprinkler droplets trace an arc through a shroud of air, which is very seldom at 100% humidity. A gentle breeze of 3 km (two miles) per hour will replace the "saturated shroud" on a typical 500 m long heap with unsaturated air every 10 minutes, and the pumping action of the sprinkler droplets will cause additional rapid air replacement. A good discussion of evaporative sprinkler losses is presented in Univ. of Florida Cooperative Extension Service Bulletin 290. Typical sprinkler evaporation at operations using coarse-drop sprinklers in Nevada-type climates (arid, temperate) is up to 15% of solution pumped on summer days and 2-4% on summer nights, averaging about 7% annually.

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 total solution pumped in summer months and 10% annually. Thus, direct sprinkler loss accounts for about 60% of the total. Use of drip irrigation can reduce but not eliminate evaporative loss.

In tropical climates, noticeable losses occur even during the rainy season. KCA's in-house experience on several tropical heap leach projects where rainfall is seasonal and up to 2.5 meters per year, is that overall annual evaporative loss from all sources, when using wobbler-type sprinklers operated 24 hours/day, is about 7% of solution pumped. Typical heap application rate is 10 l/hr/sq. m, or 88 meters per year (9 inches/day). Thus, evaporative loss of 7% is equal to 6.2 meters per year 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 meters/year. For these operations, very large solution surge ponds are required: at Sansu, Ashanti, Ghana (rainfall 2.5 meters/yr.), for a 3000 tonne/day heap leach, total pond volume was 60,000 cu meters.

Where rainfall is high and evaporation rate is low, some operations (such as at Yanacocha, Peru, altitude 3500 meters) cover sideslopes with plastic to minimize rain collection. Others (Rio Chiquito, Costa Rica - Mallon Minerals Corp) have tried to cover the entire heap during the rainy season, but this has not worked very well because of the mechanical difficulties of moving the cover.

In West 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 or hydrogen peroxide, followed by adjustment of 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 high altitude operations (for instance the Landusky-Zortman operation in Montana, now closed). 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 (Brewery Creek, Yukon; Illinois Creek, Alaska) have been able to stay in water balance because precipitation is lower than the total water requirement needed to saturate the ore.

SOLUTION APPLICATION EQUIPMENT

A variety of solution application methods have been employed, but for mainstream heap leaches the following equipment has become standard:

- Drip Emitters. Drip emitters, which issue drops of water from holes every 0.5 to 1.5 meters across the heap surface, are very common. Drip emitters are easy to maintain and minimize evaporation. The main drawback to drip emitters is that they do not provide continuous drip coverage. Thus the top one meter of the heap may not be leached very well until it is covered with the next lift. Other problems are that emitters require an intense (and expensive) use of anti-scalant, and they require 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 that they deliver a uniform solution distribution pattern, which ensures uniform leaching of the heap surface. The coarse droplet size has another advantage - 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 on a 6 x 6 meter 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 wear full rain gear to eliminate any exposure problem, but the working environment (especially in cold weather) is not as nice as with drip emitters.
- Reciprocating Sprinklers. Reciprocating sprinklers shoot a stream typically 5 to 8 meters long of mixed coarse and fine droplets. They are not considered ideal for heaps, but often find application for sprinkling sideslopes since they can be mounted on the top edge to cover the entire slope. If emitters and wobblers are used on sideslopes, they must be installed on the slope, which is a difficult and sometimes dangerous place for personnel.
- 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. 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.

For the 37 operations responding, solution application methods are summarized in the list below.

- 13 use only drip emitters
- 5 use only wobbler sprinklers
- 19 use both drip emitters and wobbler sprinklers
- 10 bury the drip emitters
- 5 use buried drip emitters between lifts
- all five "tropical" leaches - rainfall above 1500 mm per year - use wobblers.

Regardless of the systems used for solution application and management, capital and operating costs for solution handling are usually small. On the heap, header pipes up to 400 mm diameter are located every 30 to 60 meters across the heap. Material of choice for these pipes is usually HDPE (High Density Polyethylene), but sometimes it is mild steel. Distribution pipes of PVC or UV-stabilized PVC, usually 75 mm to 150 mm diameter, take off from the header pipes and are placed on similar (30 to 60 meter) spacing. From these, individual drip emitter lines up to 60 meters long cross the heap on 1.0 meter centers, or sprinkler manifold pipes (25 to 50mm PVC) up to 60 meters long cross the heap on 6 to 8 meter centers.

Total piping cost including header pipes (installed) is about \$0.60 per square meter, or \$0.05 per tonne of ore leached.

POWER COST FOR PUMPING

For the average two-cycle leach, two tonnes of solution are pumped to the heap and one tonne to the recovery plant, for each tonne of ore leached. Typically on-heap pressure for pumping barren solution is 100 psi at the pumps, and in-plant pressure for pumping pregnant solution is 30 psi. Thus, for two tonnes of solution per tonne of ore, power for pumping is 1.8 kWhr/tonne of ore and cost is \$0.14/tonne. Where heaps are very high or where evaporation is required, power consumption can approach 4.0 kWhr/tonne.

LEACH PADS AND PONDS

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 solution will flow across the surface towards collection ditches on the base or sides of the heap. Where the slope exceeds 3%, the front edge of the heap (30 to 50 meters) should be graded flat to provide a buttress to prevent heap failure.

Heaps can be placed in fairly steep-walled valleys with side slopes up to 20% (12 degrees). For long slopes above 10%, careful choice of pad material is necessary. LLDPE (Linear Low Density Polyethylene) offers a good choice because it has the ability to stretch but also has a high tensile strength, and it can be heat-welded to HDPE in flatter areas.

Valley Fill Heap Leach

A "Valley Fill Heap Leach" is a heap leach that has been built upslope from an earth dam. The containment area of the dam is filled with the stacked ore. The voids in the ore provide solution containment, and this volume serves as the pregnant solution storage pond. The ore stacked in the containment area behind the dam is usually a small part of the heap, which continues upslope and above the containment area. Thus, the dam might be ten meters high and the heap 50 meters high. A good example of a Valley Fill heap leach is Rochester, Nevada, shown in Figure 4.

Valley Fill heap leaches are used where terrain is steep and the ore must be placed in a narrow valley. They are also employed in arctic or high altitude environments as a method of keeping the process solution from freezing.

In normal leach pad construction, best design practice is to spread the solution out across the liner and to minimize solution hydraulic head to a few inches in any area. With a Valley Fill design, solution flow is concentrated and hydraulic head is high. The leach pad immediately upslope from the dam (in the solution storage area) must be built very carefully, usually with extensive sub-base preparation, double liners, and extra leak detection.

PAD CONSTRUCTION COST

A typical pad consists of several layers of material, listed from bottom to top. The ideal padsite begins as a uniformly sloping area with a grade of 0.5% to 2.0% in the direction of the process ponds. However, orebodies often occur in mountainous areas. It has been general practice to place the heaps within one or two kilometers of the orebody even if this requires extensive pad

Figure 4 Valley Fill Heap Leach - Silver Heap Leach at Rochester, Nevada. Much of the process solution is stored within the heap, behind the dam which can be seen at the downslope (left) edge of the heap.

area earthworks. The Tarkwa operation in Ghana employs a three kilometer long overland conveyor to move crushed ore to the padsite. Overland conveyors of ten kilometers or longer are common in other segments of the mining industry, and can be profitably employed to move ore to a heap leach site. It is not necessary to grade the padsite to a uniform grade of one or two percent. Internal hills and valleys within the padsite can be accommodated, as well as internal slopes up to 20 percent, provided that internal drain pipes can intercept the solution and direct it downhill to the process ponds. The cost shown in Table 2 are typical installed cost per square meter of pad surface for a padsite requiring minimum preparation. If complicated earthworks are required, these may add up to $5.00 per sq m to the costs shown in Table 2.

Ponds are installed downslope from the heap to provide storage of process solution. Usually there is a pregnant solution pond, a barren solution pond, and an overflow/storm water pond. There may be one or more intermediate solution ponds (sometimes solution is recycled from older to newer heaps to build up the gold content before processing).

Ponds are sized to permit storage of sufficient process solution so that the operators do not have to closely watch the pond levels. In addition to this "operating capacity", ponds are sized to contain solution during a several-day power outage and a major rainstorm event. Pond construction is similar to leach pad construction, except there is usually a second plastic liner with leak detection between the liners.

MINING, ORE PREPARATION & STACKING

Mining of ore for heap leaching employs the same techniques and equipment as mining of ore to feed any other process method. Where uncrushed ore (run-of-mine 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.

	CONSTRUCTION ELEMENT	COST, $/M^2
•	Preliminary earthworks - removal of topsoil, building of edge berms and collection ditches. Cost assumes minimal alterations to topography. Sometimes it is necessary to do extensive site preparation, at a cost of several dollars per square meter.	$1.00
•	150 to 300 mm of compacted clay-rich soil, engineered to a permeability of 10^{-6} cm/sec.	$1.00 - $3.00
•	Limited leak detection, usually embedded small-diameter perforated pipes placed near the lower edge of the heap and in areas of solution concentration. These "daylight" to collection sumps at the front of the heap. Leakage is usually permitted up to a certain small limit provided the area is not extremely environmentally sensitive.	$0.50
•	Plastic liner, usually 0.75-1.00 mm (30-40 mil) thick PVC, or 1.50 to 2.00 mm thick HDPE or LLDPE. The liner is delivered in rolls up to 2000 sq. meters each, and field-welded to form the total liner. The initial installation for a "small" heap leach may cover 100,000 square meters; large installations may install 500,000 sq. meters each year. An HDPE liner of 2.00 mm thickness has sufficient strength and puncture resistance to support a heap up to 150 meters high.	$3.00 - $5.50
•	Geotextile Cover may be placed above the plastic to prevent damage of the plastic by rocks in the drainage layer. The use of the geotextile is an economic tradeoff with the crush size of the gravel.	$1.50
•	Drain pipes, usually 75-100 mm perforated flexible tubing, are placed on 6 meter centers above the plastic. Where solution does not drain directly out the front of the heap, large collector pipes may also be embedded in the drainage layer.	$0.50
•	Gravel cover, up to 1000mm thick, is placed next to protect the pipes and the liner, and to provide a permeable base below the heap. Cost may be low if the gravel can be produced from the ore.	$0.50 - $5.00
•	TOTAL INSTALLED PAD COST	$8.00 - $17.00/M^2

Table 2 Leach pad component costs

Ore preparation varies widely. Run-of-Mine (ROM) ore may be hauled from the mine and dumped directly onto the heap, as shown in Figure 5. Nineteen of 36 operations surveyed had ROM heap leaches. Of these, twelve had only ROM leaches and seven had both ROM and crushed ore leaches.

At the other extreme from ROM leaches, Comsur's Comco silver heap leach at Potosi, Bolivia, crushes and then dry grinds all ore prior to agglomeration, with a grind size of 50% passing 150 microns (100 mesh). Three operations (Ruby Hill, Barney's Canyon and Castle Mountain), grind high grade ore and reblend it with the ore stream going to the heap leach (at Ruby Hill and Castle Mountain, the high grade is leached in agitated tanks to partially recover the gold).

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. Such a system is shown in Figure 6. Many ores are crushed and then either truck-stacked or conveyor-stacked without agglomeration. For these harder ores, crushing is usually done using a jaw crusher followed by one or two stages of cone crushing.

Figure 5 Truck dumping an upper 10 meter lift of run-of-mine ore on top of a lower lift that has already been leached.

Figure 6 Agglomerating drum and conveyor stacking system with 6 meter high heap at Ity, Ivory Coast.

Agglomeration

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

- At the simplest level, 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.
- At the next level, the ore contains amounts of clay or fines that 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. Operations that intentionally employ drop points or slide chutes are Barney's Canyon and the La Quinua operation of Yanacocha.
- Where ores are nearly pure clays, such as the laterite/saprolite ores in tropical climates, Drum Agglomeration is usually employed. The ore is first crushed finely enough (typically 25 to 75 mm) to form particles that can be a stable nucleus for round pellets. 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. Drum size and throughput are a function of several factors, but typically a 3.7 meter diameter, 10 meter long drum can process 750 tonnes of ore per hour. A 2.5 meter diameter drum can process 250 tonnes/hr. At the Tarkwa mine in Ghana, two 3.7 meter drums are installed to process up to 20,000 tonnes ore per day.

Of the 24 crushed-ore operations responding, 11 use drum agglomeration, 5 use belt agglomeration, and 8 do not agglomerate. Fifteen use conveyor stacking systems, the remainder stack with trucks. All the operations that use drum agglomeration stack with conveyor stackers.

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. Truck dumping causes segregation of the ore - the fines remain on the top surface, and the coarse material rolls to the base of the lift creating a highly permeable zone at the base. 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. Short lifts also result in less segregation. At Sterling, Nevada the problem was avoided by stacking the ore in 1.5 meter (5 ft) lifts but leaching in 6 meter (20-ft) lifts.

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 two meters. To mitigate this problem, most operations rip the ore after stacking (but prior to leaching). Number of ripper passes is important; usually it is four passes in a criss-cross pattern. Some operations (Candelaria, Nevada) practised building an elevated truck roadway that was then bulldozed away. However this requires substantial bulldozer traffic on the heap surface, which can lead to permeability problems for some ores.

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 on small operations than on large ones, because the roadway width is nearly the same regardless of the daily production rate. For a heap leach of 5000 tonnes/day, the roadways on the heap can tie up one month's ore production, with a value of $1.8 million. A conveyor system that stacks ore from the base of the lift can reduce 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. For operations of 100,000 tonnes/day, truck stacking is more flexible and may be less capital intensive than a conveyor system.

Conveyor Stacking
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 meters long. At Tarkwa, Ghana, a 3 km overland conveyor is used.
- A series of eight to fifteen "grasshopper" conveyors to transport the ore across the active heap area. Grasshoppers are inclined conveyors 20 to 30 meters 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 to 50 meters long, with a retractable 10 meter conveyor at its tip. Wheels, discharge angle, and stinger position are all motorized and are moved continuously by the operator as the heap is built.

Figure 7 shows a typical stacker system in operation. Stackers are usually operated from the base of the lift (as shown in the figure) but may be located on top of the lift, dumping over the edge. Inclined conveyors can be installed up the sides of the lower lifts, and the stacking system can be used to build multiple-lift 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.

Stacking systems like the one shown in Figure 7 can be used for heaps processing up to 50,000 tonnes of ore per day, but beyond that the size of the stacker (and the bearing pressure that is exerted by the wheels) becomes prohibitive. Typical cost of a complete stacker system with a 900mm (36-inch) wide belt for a 10,000 tonne/day heap leach operation, including the stacker and

Figure 7 Stacking system for capacity of 10,000 tonnes ore per day. Elements include stacker with extendable stinger; follower conveyor; cross conveyor; and several grasshopper conveyors.

follower conveyors, and ten grasshopper conveyors, is $1.5 million (delivered and installed at a typical developing-country heap leach site). Three hundred meters of overland conveyor connecting the stacking system to the crusher/agglomeration system cost an additional $500,000.

Figure 8 Rahco stacker building a 12 meter lift by tripping the ore over the advancing edge. The stacker can climb ramps and turn sharply to fit project requirements.

For operations stacking very high tonnages, large stackers can be mounted on caterpillar tracks to reduce ground pressure. Rahco International, Inc. (Spokane, Washington) makes a unique stacker, which is ideally suited to building large heaps at high tonnage rates. The stacker, shown in Figure 8, has individual drive adjustments so that it can climb up ramps to the next level and make sharp radius turns.

RECOVERY OF GOLD AND SILVER FROM HEAP LEACH SOLUTIONS

Other chapters in this book cover the details of recovery plant operations, so this section will be limited to a brief summary of heap leach plant operating results. Basically, gold and silver can be recovered from solution by contacting the solution with granular activated carbon in columns (CIC), followed by stripping of the carbon using a hot caustic solution. This caustic solution is processed in electrolytic cells or a zinc dust precipitation vat to recover the metal, which is then melted to produce a doré (impure bullion) bar. A CIC plant is shown if Figure 9. Where the ore is high in silver, typically with a recoverable silver content of more than 10 grams per tonne (0.3 oz/ton) of ore, Merrill-Crowe zinc precipitation is used instead of carbon adsorption. In this process the solution is clarified and de-aerated, then contacted with zinc dust to precipitate metallic gold and silver. This precipitate is then melted to produce bullion.

Of 34 operations reporting, 28 use carbon in columns (CIC) for adsorption of gold and silver from leach solutions, and six use Merrill-Crowe zinc precipitation plants. Three of the six using zinc precipitation reported at least 9:1 silver:gold in the bullion. Another, with 2.6 silver to 1.0 gold, produces leach solutions that are very high grade in both gold and silver content, thus justifying the choice of zinc instead of carbon. The other two process low grade gold solutions more typical of CIC plants.

Average pregnant solution gold content at the 28 CIC operations is 0.70 grams gold per tonne of solution. For these operations, loaded carbon averages 3900 grams gold per tonne of carbon, with six above 5000 grams gold per tonne of carbon. Six of these regenerate 100% of the carbon after each strip cycle, eight regenerate only 50% of the carbon per cycle, three do not regenerate. Three "high grade" CIC operations, all in Africa, reported pregnant solution grades of 3.5, 3.0 and 11.0 grams gold per tonne. These operations reported carbon loading of 8000, 6000 and 28,000 grams gold per tonne respectively. Stripped carbon from all operations averages 90 grams gold per tonne with 50% reporting in the range of 50 to 150 grams gold per tonne.

Figure 9 Five-stage carbon adsorption column plant (CIC plant) at Glamis Gold's San Martin, Honduras project. There are two parallel column trains (one is behind the other in this view). The plant can process up to 900 cu m of solution per hour, and is sized for an operation that processes up to 20,000 tonnes of ore per day.

DESIGN CONSIDERATIONS FOR RECLAMATION AND CLOSURE

Once 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 three years), during which time one tonne of wash water or recycled treated process solution is applied. Heaps are then capped, and ponds are filled and capped.

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 "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 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 since 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 flowrate of the heap effluent decreases to a manageable level (or to zero in arid environments). Once the flowrate is 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 as long as is necessary.

A two million tonne heap of ore covering 90,000 sq. meters (average thickness 14 meters), located at Goldfield, Nevada, was recently closed with a clay/soil cap. Heap effluent gradually and steadily declined to 2.0 liters/minute after 36 months. Periods of intense above-average rainfall did not affect effluent rate. While this is a small and not very high heap, scaleup of this data should be applicable for preliminary design purposes.

Worldwide practice ranges 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 applicable in other situations. Heap closure needs to be addressed in the feasibility stage of the project.

Typical cost of closure, including three years of heap washing, is \$0.50 per tonne of ore stacked. This can be accumulated as a deferred operating cost. However, for U.S. heap leaches, regulators may require a closure bond to be put up at the beginning of the project. The amount of the closure bond is calculated using "government-defined" guidelines that typically result in a bond of \$1.00 per tonne of total ore to be placed. This adds a generally prohibitive line item to capital cost, which is one of the reasons why new project activity has declined in the U.S. in recent years. (This item has not been included in the capital cost summary presented in Table 3).

CAPITAL COST

Capital cost for a small "basic" heap leach (3000 tonnes/day) with minimal infrastructure at a developing-country leach site is typically \$3500 to \$5000 per daily tonne of ore treated, with the higher cost attributed to high logistics expenses at remote sites such as central Asia. Larger operations (15,000 - 30,000 tonnes per day) cost \$2000 to \$4000 per daily tonne, but may commonly reach \$6000 where "corporate culture" calls for process redundancy and infrastructure. Use of a mining contractor and/or a crushing contractor is common, and may eliminate the capital costs for these line items. Capital costs for some recent installations are shown in Table 3.

- Glamis Gold's San Martin heap leach (built 1999) had a published capital cost of \$27 million (Glamis 1999 Annual Report) and began operations at 13,000 tonnes of ore per day (equal to \$2,100 per daily tonne). Ore was crushed, agglomerated and conveyor stacked. Mining equipment was transferred from another operation at nominal cost; the operation was designed with excess capacity to allow for rapid expansion to 20,000 tonnes per day.
- Canyon Resources Briggs Mine in Southern California, built in 1996, cost \$29.9 million for 9,500 tonnes/day (Marcus, 1997). This cost included \$4.2 million for permitting, and a flowsheet that included 3-stage crushing. Mining equipment was leased. Adjusted for inflation to year 2002, Briggs' capital cost equaled \$3,600 per daily tonne.
- Anglo American's Yatela Project in Mali started up at an annual rate of 7,000 tonnes per day, and cost about \$8,000 per daily tonne (actual published capital cost was higher, but included extraordinary items).

Capital cost breakdown is shown in Table 3 for "typical" developing-country, remote sites with minimal infrastructure and minimal redundancy. Each operation, of course, will have a unique mix of capital cost line items.

OPERATING COST

Table 4 shows the breakdown of direct cash operating costs for the 27 operations that reported results for this chapter. (Direct Cash Operating Cost as used here includes all site costs including site and local office support costs, property taxes, import duties and fees. It excludes income and severance taxes, finance costs, royalties, product marketing costs, and depreciation/depletion). These operations had an average production rate of 15,800 tonnes/day. Average mining cost per tonne of material moved was $1.16, and average waste:ore ratio was 1.68:1. Labor rates varied widely, with seven operations reporting costs below $2.00 per hour, and thirteen above $15.00 per hour. Heap leaching is not a labor-intensive process, and where labor costs are low, logistics costs are usually high. Therefore there is not an obvious correlation between labor cost per hour and total operating cost per tonne.

HEAP LEACH CAPITAL COSTS		
	3000 tonnes/day	15,000 tonnes/day
Feasibility / design studies / permitting	US$ 400,000	US$ 1,000,000
Mine equipment	2,200,000	9,900,000
Mine development	600,000	1,200,000
Crushing plant (2 stage)	1,200,000	3,500,000
Leach pads/ponds	1,000,000	4,600,000
Agglomeration/stacking system	1,000,000	3,500,000
Process pumps, plant, solution distribution piping	1,100,000	3,500,000
Laboratory	300,000	500,000
Infrastructure (power, water, access roads, site office and service facilities)	1,700,000	7,500,000
Owner's preproduction cost	700,000	2,800,000
EPCM (engineering, procurement, construction management)	900,000	2,000,000
Import duties / IVA	800,000	7,000,000
Equipment / materials transport	600,000	2,100,000
Initial operating supplies	300,000	1,500,000
Working Capital	1,200,000	3,000,000
TOTAL	14,000,000	53,600,000
CAPITAL COST PER DAILY TONNE	US$ 4,700	US$ 3,600

Table 3 Heap Leach Capital Costs

REPORTED DIRECT OPERATING COSTS			
	Mining, $/tonne	Other, $/tonne	Total $/tonne
Total 27, average	3.11	4.00	7.71
Seven lowest, avg	2.50	0.88	3.38
Six highest, avg	5.90	8.17	14.07

Table 4 Direct cash operating costs for the 27 operations which reported costs for this chapter.

Operating cost is not very sensitive to the size of operation. Published direct cash operating cost for Barrick's Pierina mine (85,000 tonnes/day) is $3.93 per tonne, including $0.87 for mining. A recent study of an on-going operation in Africa concluded that increasing production from 4,300 tonnes/day to 13,000 tonnes/day would decrease costs (excluding mining) from $5.80/tonne to $5.10/tonne.

TYPICAL HEAP LEACH OPERATING COSTS, US$/tonne			
	3,000 tonnes/day	15,000 tonnes/day	Typical Nevada 30,000 tonnes/day
Mining (Strip ratio 2.5:1, cost/tonne of ore)	3.00	2.00	1.70
Crushing, Primary	0.40	0.20	0.20
Crushing, second plus third stage	0.50	0.40	0.20
Crushing (fourth stage, to 1.7mm (10 mesh)	0.80	0.80	-.00
Agglomeration/stacking	0.20	0.10	0.10
Leach operations (incl sprinkler supplies)	0.50	0.30	0.20
Recovery plant operations	1.50	1.30	1.40
General site maintenance	0.60	0.30	0.30
Cement for agglomeration (10 kg/tonne)	1.00	1.00	-.00
Cyanide, lime, other reagents	0.30	0.30	0.30
Environmental Reclamation/ Closure	0.50	0.50	0.50
General & administrative, support expenses	1.50	0.50	0.30
TOTAL SITE CASH OPERATING COST	10.80	7.70	5.20

Table 5 Typical Heap Leach Operating Costs

Average operating costs for "typical" heap leaches can be broken down as shown in Table 5. Costs are shown for ores that need crushing, agglomerating and conveyor stacking. Not all items in the list are appropriate for all operations; the right-hand column shows costs, that are more typical of a 30,000 tonne/day, coarse-crushed, unagglomerated Nevada heap leach.

TRADEOFF BETWEEN LEACHING IN HEAPS AND IN AGITATED TANKS

The alternative to leaching of ore in heaps is to grind the ore to a fine pulp, and to leach it as a water slurry in agitated tanks. 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 leaching normally has significant capital cost advantages, so it is favored over agitation leaching where operating factors are identical.

Combined flowsheets are also utilized. Of 37 operations reporting, four use some form of grinding or grinding/agitation leaching for part of the ore stream going to the heaps. Homestake's (now Barrick's) Ruby Hill, Nevada, operation partially leaches high grade ore in agitated leach tanks, filters the tailings and combines them with crushed ore going to agglomeration and heap leaching. Castle Mountain (Viceroy Gold) uses a similar flowsheet. Barney's Canyon (Kennecott) wet-grinds part of the ore stream, but does not leach it before adding it to the agglomerator feed. Good discussions of these combined flowsheets can be found in Lehoux (1997) and Jones (2000). As presented in the paper by Lehoux on Ruby Hill, direct operating cost of the grind/leach portion of the operation was $4.98/tonne. Analysis of the capital and operating costs presented in the paper indicate that the heap-leach-only option may have been more economic.

Comsur's Comco silver heap leach dry grinds the entire ore stream to minus 105 microns (150 mesh) prior to agglomeration. In its third year of operation, Comco switched to wet grinding but it could not control water balance in the agglomerating drum, so it switched back to dry grinding.

Six of the heap leach operations reporting also have agitated leach plants for oxide ore that run as separate "stand alone" facilities. Ore is diverted from one to the other depending on grade (or in one case, depending on sulfide content). Average nominal "cutoff grade" to the mill for these operations is 2.30 grams gold/tonne (0.067 oz/ton), and cutoff grade to the heap is 0.41 grams gold/tonne (0.012 oz/ton). In practice, the cutoff grade to the mill is a function of the ore available on a daily basis - the agitated leach plant is fed to its capacity provided the ore is of reasonable grade.

CONCLUSION

Although the concepts of precious metals heap leaching are simple, the practices have substantially evolved over the past 35 years. Early choices for pad materials, sprinkling 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. There is now a large resource of successful operations from which to draw the experience needed to optimize the process. Heap leaching is expected to maintain its place as one of the principal tools for extracting gold and silver 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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