Lessons learnt from heap leaching operations in South America—An update

by B. Ulrich*, H. Andrade†, and T. Gardner†

Synopsis

The basis of this paper is a compilation of work in the design and construction of copper heap leach facilities, and interviews with various heap leach operations personnel in Chile and Peru. The purpose is not to highlight specific mines and their performance, but rather to discuss geotechnical/civil features of copper heap leach facilities that function well, as well as features that do not.

During the 1990s several copper heap leach facilities were brought on-line in South America. Many of these facilities have now been operational for a number of years during which time the operators have been able to monitor the performance of their heaps. This paper serves as a compilation of operators' experiences, and provides a discussion of the lessons learnt over the past decade. Several key geotechnical issues are examined, focusing upon the integrity of the ore, drainage material and pipe network, along with the success of inter-lift liners. This conference provides a timely update of the original paper (Burkhalter *et al*, 2002).

Introduction

In recent years, production of extremely pure copper from solvent extraction and electrowinning (SX/EW) of solutions obtained from leached oxide and sulphide ores has gained popularity as an efficient recovery method in a low cost market. This technology is especially prevalent in the high, dry deserts of western South America, where several of the world's largest copper mines are situated. The climate and ores found in the region are well suited for the recovery of copper through the construction of a relatively low cost pad, solution collection system and associated SX/EW facility. Extensive design efforts and investments have been made in the region to develop low capital cost and efficient processing plants, resulting in some of the lowest production cost mines in the world. Key to the success of these mines is the performance of the heap leach facility and associated fluid collection system and their ability to recover copper. The focus of this paper is a review of the geotechnical aspects of several of the South American operations and to learn what aids in the ultimate goal: maximum copper recovery.

Basic principles

The basic principle behind copper heap leaching technology is simple: extract the copper from the ore using physical contact with a leaching solution to put the copper into solution. The impregnated solution is collected and processed to remove the copper and the cycle is repeated. To enhance metal recovery, modern leaching processes use one or more of several available methods including solution recycling, chemical and biological reactants and/or physical alteration of the ore. It should be noted that while these methods improve the metallurgical response of the ore, they also change its geotechnical properties.

There are several types of heap leach facilities in use in the South American copper industry. For the purposes of this paper, they are categorized as follows:

- *Dump leach facility*—These facilities use run-of-mine (ROM) ore placed in a defined topographic area and rely on natural low permeability barriers underlying the stack to control the flow of solution. Material is usually placed in lifts greater than 10 metres and total heights reaching 200 metres or more.
- *ROM leach pad*—These facilities use ROM ore placed on a designed pad that is lined with a low permeability layer and fitted with a solution collection system. Material is usually placed in lifts of 7 to 8 metres and total heights ranging from 100 to 150 metres.
- *Permanent heap leach pad*—These facilities use physically altered ore placed on a designed pad that is lined with a low permeability layer and fitted with a solution collection system. Material is usually placed in lifts of 4 to 7 metres and total heights ranging from 80 to 100 metres.

* *Knight Piésold (Pty) Ltd, Rivonia, South Africa.*

† *Knight Piésold, Santiago, Chile.*

- *On/Off heap leach pad*—These facilities use similar pads and collection systems as the permanent pad but each lift is removed after it has been leached. The 'spent' ore is then placed in large lifts in a defined topographic area.

The facilities discussed in this paper consist of the latter three types. While the civil/geotechnical design criteria for each of these will differ depending upon site-specific constraints and ore types, the following points are universal:

- The pad should be laid out to accommodate the loading method, ore production rate, leach cycle, and local topography
- Lift heights are set to optimize recovery and for ease of operations
- Constituents of the leach solution, water, acid, organics, etc. need to be conserved as much as possible
- Designs should be produced endeavouring to minimize mingling of process solutions and to withstand a designated storm event
- The heap must be stable for both static and pseudo-static conditions.

In principle, all of the designs reviewed met each of these requirements, but the design details varied from pad to pad. The physical components of a heap leach facility important to this paper are shown in Figure 1. Table I lists the key geotechnical components in the design of a typical pad and presents the range of materials used in Chile and Peru.

Results of investigations

For simplicity, the topics reported herein are arranged in the order they would generally be constructed, that is, from the ground up. Observations, comments and problems were categorized into one of the following topics:

- Pad re-grading
- Liner sub-grade
- Geomembranes
- Drainage/protective layers
- Internal solution collection pipework
- Ore permeability
- External solution collection
- Solution delivery
- Inter-lift liners
- General.

Discussions, observations, comments and problems regarding the geotechnical/civil components of the pads identified as part of this study are presented below.

Pad re-grading

Pad re-grading may be required to create or enhance gravity flow of fluids away from the heap and into a solution conveyance system. Pad re-grading on the facilities studied varied from minor shaping of a relatively flat area, to large valley fills (>30 m). Grading plans were developed to enhance local drainage control, and/or to accommodate loading equipment. Key factors considered within the designs were the settlement of fill materials, maximum slopes acceptable for pad stability and/or operation of loading equipment.

For the sites reviewed that required major re-grading, the most common and economical material used for fill was sterile mine waste from current or past operations. The materials were generally classified as rock fill, and as such, the majority of their settlement occurred during construction. Compaction was achieved by placing the material in 0.5 to 5 metre lifts, depending upon the overall thickness of the fill (i.e., thicker lifts placed at the bottom of a large fill, with increasingly smaller lifts as the material approached final grade). While reported fill settlement was within design limits at the mines visited, careful monitoring is advised for any pads constructed upon fills. Monitoring should continue as the heap height increases.

Several of the facilities reviewed had designed cells with dividing berms or trenches to aid with solution separation. While almost all operators interviewed agreed that solution separation enhances recovery, several expressed a preference for trenches due to interference between the berms and the stacking equipment. For some operators expanding their pads, original designs that included berms were changed to incorporate trenches.

One other common reason for re-grading of the pads was to decrease the slope on the downhill toe of the heap thereby reducing the risk of a block failure along the liner/soil interface. At several facilities the first 100 to 150 metres into the pad was kept at less than 1 or 2% grade. Depending upon the amount of re-grading required, some designers found it

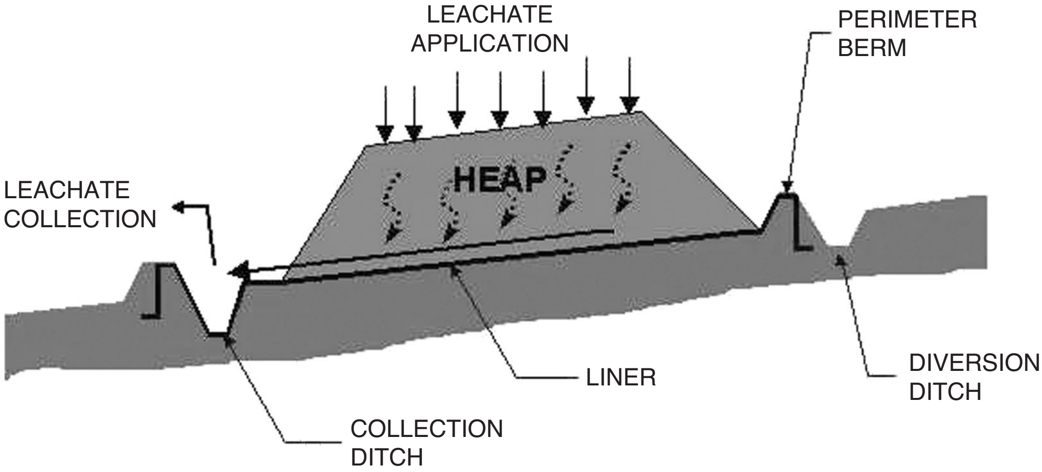

Figure 1—Simplified schematic cross-section through a heap leach facility

Table I

Geotechnical components of the pads reviewed

Component	Range of Materials/values	Remarks
Pad re-grading	Minor shaping of natural terrain to major fills (>30 m) within steep valleys	Controlled by existing topography and limits of ore loading equipment.
Liner sub-grade	Compacted *in situ* materials or imported fine-grained material including native silts and clays or tailings	Controlled by whether or not sub-grade is to be considered as a soil liner and the amount of large angular material within the pad area.
Geomembranes	0.5 to 2.0 mm HDPE, LLDPE or PVC, textured and smooth	Controlled by the quality of the sub-grade and pad stability.
Protective layer	None to 200 mm of fines from crushing operation	Needed if drainage layer or ore is detrimental to the geomembrane.
Drainage layer	None to +1 metre of processed drain rock	Controlled by the permeability of the ore.
Internal collection pipework	50 to 600 mm corrugated HDPE pipe, both double and single walled	Spacing is controlled by the permeability of the ore. Methods of coupling varied.
Ore permeability	10^{-3} to 10^{-6} cm/s	Varies with normal load and leaching.
External solution collection	300 mm to 900 mm HDPE pipe or open HDPE-lined trenches	Pipes were used to limit evaporation losses. However, trenches were more common.
Solution delivery	HDPE pipe with drippers and sprinklers	Many mines combined sprinklers and drippers.
Inter-lift liners	0.3 mm PVC, 0.5 mm LLDPE, and compacted ore	Effects on residual copper recovery debated.

more economical to place textured liner to improve the factor of safety against a sliding block failure, rather than re-grading extensive areas of the pad. Several of the operators preferred the inclusion of a toe berm, since in addition to any cost savings, it also allowed for greater control of the exiting solution.

Liner sub-grade

The material immediately underlying a geomembrane is termed the liner sub-grade. The sub-grade material is an integral part of the liner system, even if it not considered as a secondary liner. All operators agreed that the performance of an expensive geomembrane liner is highly sensitive to the quality of the sub-grade it rests upon. Re-grading of the pad sites reviewed involved the exposure of several types of native materials, and/or the use of coarse mine waste. Successful designs included clear and detailed specifications for the pad sub-grade based upon site-specific conditions. Key issues addressed included; the compaction and resultant permeability of the materials, the resultant friction angle at the sub-grade/liner/ore interface with the geomembrane, settlement of any fills, and the quality of the surface for geomembrane placement.

The permeability of the sub-grade is an important issue if it is considered part of a composite liner system. The interface friction angle between this material and the geomembrane will control the stability of the pad. Differential settlement of fills used in re-grading the pad is an important issue, or if it is significant enough to alter the intended flow of fluids within the facility. In many cases though, the most significant issue with the sub-grade was the quality of the top surface for geomembrane placement. In most of the pads in the Atacama Desert, the sub-grades were natural silty sands and gravels that exhibited relatively low permeability and smooth surfaces once they were scarified and compacted, hence requiring little or no material processing. The pads reviewed that were built upon coarse mine waste fills required importation and/or processing of fine material to achieve a suitable sub-grade, with one of the most economical materials being copper tailings. Other operations successfully used imported native silts and sands.

Geomembranes

The term geomembranes is applied to synthetic lining materials typically consisting of any of a number of types of plastic polymer. The incorporation of geomembranes in the ROM, Permanent and On/Off Leach Pads of western South America was unanimous. Almost all sites used Polyethylene (PE) liners as the primary liner beneath the heap. The key issues for the geomembranes included; resistance to puncture, the interface friction angle with materials above and below them, and resistance to ultraviolet radiation, especially at the high altitude mines. Several sites used Linear Low Density PE beneath the pad for its greater flexibility and High Density PE on exposed areas for its higher ultraviolet resistance with great success.

One common problem discussed regarding the geomembranes was the care of the exposed areas of liner following construction. Most operators emphasized that all employees involved with the pad should be inspired to 'own' the liner. One suggested that the operations staff should be trained on the 'dos and don'ts' around the liner, just as they are for any piece of equipment. Care of the geomembrane should include protection of the surface when placing any objects on it, not allowing heat sources near the liner (cigarettes, welding equipment, etc.) and placement of rub sheets where flows cascade on to the surface.

Drainage/protective layer

The drainage and/or protective layer is the material that is placed directly upon the geomembrane. The use of a designed drainage layer is a key component of a successful heap. The layer serves two purposes, to aid in evacuation of the solution from the heap, and to protect the underlying geomembrane against excessive build-up of fluid pressure. Both considerations are important when selecting a material.

Several heaps reviewed incorporated a defined drainage layer of processed mine rock or natural gravels beneath the ore. One proven method involved crushing and screening sterile mine rock and using the fines for a protective layer and the coarse fraction for the drainage layer. Other sites successfully used spent leach ore or tailings from historic operations as a protective layer and secondary crushed ore as the drainage layer.

The authors wish to emphasize that it is good practice to design the drainage layer to filter the ore. Conventional filter and drainage criteria developed for zoned earth dams are applicable to heap leach pads. The main requirements for a candidate filter material are as follows:

- The filter material should be more permeable than the base material in order that hydraulic pressures do not build up
- The voids of the filter material must be small enough to prevent the base material from migrating into the filter, causing clogging and failure of the filter system
- The filter should be non-segregating or placed in a non-segregating manner to ensure a homogeneous and uniform placement of the material
- Filter material particles must be prevented from movement into the slotted or perforated drainage pipes, or additional coarser filter zones added if necessary.

Designing the drainage material to meet these requirements will improve the performance of the heap. If a sufficient quantity of proper material is not economically available, one should at least invest enough to cover the main collection pipes and other key areas of the heap. Also, one needs to consider the degradation of the drain material and ore under leach when completing a filter design. Several years of acid leaching may significantly change the gradation of the drainage material, and hence, its ability to filter and drain the ore. Similarly, the gradation of the ore may change under leach, thus, a different sized filter may be required after some time. If possible, laboratory modelling should be performed during the design stage in order to estimate the leach-altered properties of the ore and drainage layer.

As with any component of the pad, cost is a major issue to operators. Processing drainage layers to meet stringent specifications can be quite expensive, but the cost of failure of the heap to perform as designed can be greater. Careful study and design is recommended to determine the balance between quality and cost. It was pointed out that a proper drain does more than keep the heap stable by reducing hydrostatic pressure on the liner, it keeps the copper flowing to the plant.

At mines where on/off pads were used, some operators expressed concerns over the small layer of ore left on top of the drainage layer after the removal of a lift. This thin layer was usually very compacted and not very permeable. Solutions included scarifying and cleaning the area with a roadgrader or in one case, removing a few centimetres of drain material each time the ore lift is removed, before eventually replacing the lost material. It was noted that on/off pads provide the opportunity to review fines migration into the drainage layer, and operators are encouraged to perform studies evaluating the effectiveness of their particular drain.

Internal solution collection pipework

Slotted or perforated pipes are commonly installed within the drainage layer. In combination with the drainage layer, the solution collection pipework is the lifeblood of the heap. If the solution cannot be readily removed from the pad, inventories within the heap increase, flows to the plant decrease and copper production drops, not to mention the stability and environmental concerns associated with the increased hydrostatic pressure within the heap and on the liner. All operators agreed that the design and maintenance of a effective pipe collection system is instrumental in the successful operation of the heap. Most designs reviewed followed the same principle: a pattern of small diameter (50 to 150 mm) perforated corrugated polyethylene tubing (CPT) either exiting the pad or connecting into a network of larger diameter (200 mm to 600 mm), more robust CPT or HDPE pipes.

Some facilities used non-standard couplers for the CPT, and a few of these experienced problems with pipes pulling apart after placement of the ore. This defeats the purpose of the pipe—to maintain an open pathway for solution to exit the heap. In addition, the concentration of flow around the damaged pipe may lead to increased hydraulic gradients through the drain layer and possibly, migration of fines. Non-standard couplers used included fabricated PVC tees for HDPE pipes, and nylon ties and rope, some of which showed evidence of physical and/or chemical failures. While more expensive, using the manufactured CPT couplers, tees and wyes, and proper HDPE ties provided a good joint that generally did not fail. This is important even for the small pipes. One gold mine in Chile has used a non-standard coupling method with success. They coupled their small (75 mm) flexible CPT by cutting the end of one pipe along its axis, squeezing it to a smaller diameter and placing it inside the other uncut pipe. The corrugations locked together and the pipes held together under loading. This connection worked, whereas joints with the cut pipe placed on the outside tended to fail during loading.

All operators agreed that crushing of pipes under the load of the heap should also be considered in the design. Several researchers and pipe manufacturers have performed laboratory tests that modelled in-heap conditions and have found that the small pipes will maintain a flow path beneath the heap, even under simulated loads of 100 metres or more of ore. These pipes did change their shape but in almost all cases, maintained a similar opening size. Larger diameter (>200 mm) pipes were found to deform, but design should consider the effect of arching of the overlying soils and deflection of the load from the pipe to the drain layer.

Some operators pointed out it is of equal importance to care for the pipes from the time they are installed until the ore is placed on top of them. Traffic must be minimized directly above a pipe, or sufficient cover placed to protect it against the wheel/track loads of equipment. If not properly cared for, pipes can easily be crushed.

One relatively simple way suggested to increase the efficiency of the drainage system is to increase the amount of small pipes within the heap. It is well worth a review of the cost of decreasing the spacing on the pipe pattern vs. the cost of improving the drainage layer. Pipe spacings of 3 to 5 metres may keep the fluid levels within tolerable limits, and additional pipes would increase solution recovery, and hence the rate at which it gets to the plant. Also, it was recommended to place the small pipes at an angle to the slope direction (fall line) to increase the efficiency of the system.

With regard to migration of fines from the ore into the collection piping system, most operators said their systems were performing as designed, i.e., minimal solids were reporting to the ponds. However, a few operators reported problems with plugging of the small pipes and one reported a sinkhole in the pad above where a large pipe had failed. These failures emphasize the need for quality drain materials, the use of proper pipe connections, careful construction procedures, and damage control during loading.

Ore permeability

One other controlling factor in the efficiency of the heap is the permeability of the ore, or the rate at which the ore will allow leaching fluids to drain through. It is also termed 'hydraulic conductivity'.

Every mine runs numerous column tests to estimate recovery parameters. These tests also give valuable data on the permeability of the ore. However, it was suggested that the permeability of the ore should also be reviewed both before and after leaching, and as the load increases on the heap. An in-depth study using a permeameter that allows for load simulations was recommended as part of the design study. The permeability of the ore, which may be acceptable both before and after leaching in a column test, will decrease when a load is applied, and as the leach time increases (i.e. as chemical reactions change the geotechnical properties of the ore). One mine reported data showing that even though ore that had been leached under one cycle had a satisfactory coefficient of permeability at loads of up to 90 m, a sample of ore that had been leached through two cycles (i.e. the underlying lift) did not.

External solution collection

Once exiting from the heap, the fluids must be safely and efficiently conveyed to the process ponds. Most operators agreed that flexibility in controlling the solution as it exits the pad is an important key to a successful heap. The more control, the better, and systems allowing operators the possibility of re-routing the fluids was deemed most beneficial.

A majority of the ROM and permanent pads reviewed used cells within the pad to control loading and leaching of the ore. The solution from each cell was concentrated in a low spot and either piped or trenched into an external solution conveyance system. Flow concentration also allowed for easy sampling of the copper concentrations. For the pads studied, simple methods to allow sampling and redirecting the flow worked best. Simple ports in the pipes, or platforms to allow dipping of the trenches were common. Once analysed, the operator could decide where best to direct the flow. One useful example of a simple system included pipe exiting the cell and spanning two trenches (one for low grade solution and one for high grade solution). The end of the pipe was fitted with a 30° elbow emptying into the far trench. A hole on the top of the pipe was aligned with the near trench. The operator could then sample as often as he wished by dipping the stream and then, by simply rotating the pipe, direct flow into whichever trench the grade dictated.

Allowing solution to sheet flow into an open trench was most common method in the on/off facilities reviewed. Solution collection was aided by small (50 to 100 mm) CPTs that open ended into the trench. This system functioned well on a global scale, but there was little or no flexibility in directing solutions of higher or lower grade to a designated area.

Once outside of the pad, some operators preferred to have the solution conveyed in HDPE pipes or placed in HDPE lined trenches to obtain a double lined containment system. The pipes could easily be observed for leaks and evaporation and temperature changes within the solution were minimized. Open HDPE lined trenches for the solution was also practised, but leak detection was more difficult.

Solution delivery

Application of leaching fluids to the active portions of the heap is critical to the successful operation of a heap leach facility. This application is typically completed using a network of pumps, pipes, tubing, valves and irrigation drippers or sprinklers. Occasionally, operators will combine drippers and sprinklers.

Flexibility was also a key concern for the solution delivery system. Most facilities were designed with an assumed typical leach rate. Raffinate pumping systems were designed to deliver this rate to the heap and with consideration of physical constraints of the system. In most cases, the systems worked as designed. However, several operators said they would like to have the capability to vary the actual leach application rate to suit the particular ore characteristics and available area. They suggested that designs should include options to change or add equipment, should the necessity develop to vary the leach application rates and patterns.

Several facilities experienced problems with failed risers used to deliver solution to the heap. In many cases, the solution delivery system main header was located on the downhill side of the facility, either within or near the solution collection system. Several instances were reported where the risers failed, causing erosion or localized sloughing failures on the face of the heap. While these failures were usually not detrimental to the overall performance of the facility, they nevertheless required remedial actions and sometimes affected production by blocking or delaying solution collection. All operators agreed that using high strength pipe for the risers was good practice.

Inter-lift liners

When heaps consist of low permeability ore, considerable time may be required for fluids to migrate to the base of the heap. One manner of addressing this problem is to shorten the distance fluids must flow by constructing inter-lift liners.

Inter-lift liners and their utility are a topic of discussion at many facilities. Opinions varied as to whether or not they improved the overall economics of the heap, with most of the debate focusing upon the value of the residual copper remaining in the lower lifts. This is a very site-specific question and is best answered by specialized field and laboratory metallurgical testing. However, with consideration of solution control, inter-lift liners are very useful. There is no doubt that they reduce the amount of time it takes to recover the solution once it is placed within the heap. For the facilities reviewed, two types of liner were used: thin plastic (0.3 to 0.5 mm) or compacted ore. Both types were successful in redirecting flow within the heap. At the mines where the ore could be compacted to achieve a sufficiently low permeability barrier, the operators preferred compaction to the installation of plastic. One mine achieved a satisfactorily low permeability simply re-grading and compacting the surface to 98% of the maximum Modified Proctor Density. One of the mines could easily monitor the flows coming from the lower lifts, and reported these flows to be negligible.

The inter-lift liners observed also included a system of collection pipework similar to that installed at the base of the heap. Most of the mines that used inter-lift liners employed a conveyed stacking system that included a radial stacker. The operators found that trained personnel could work under and around the stacker and install the small pipes. Larger collection pipes were put in trenches at the edge of the cells, installed well in advance of the stacking system. It is recommended to use as much care in the design and construction of the inter-lift liner pipe network as one would for the base. Failed inter-lift liner pipes can be just as detrimental to production, and can lead to stability problems if left unchecked.

One important observation from the mines visited and other metal leach facilities: simply placing inter-lift pipework without a low permeability barrier does not significantly aid in solution recovery. A barrier is required to direct solution to the pipes.

General comments

In addition to the above comments on specific components of the facility, operators interviewed had general comments that merit reporting:

- The heap leach facility is the heart of an SX/EW operation. A lot of time and effort is spent designing the mine and process recovery plant, resulting in ever-improving facilities, but many times the heap leach pad is not given the attention and investment up front that it deserves. The best mine plan and most efficient SX/EW plants in the world will be hindered if the copper cannot be dissolved and recovered within the heap. The heap leach pad cannot be 'fixed' or 'upgraded' after construction. What is initially designed and built must be lived with for the life of the mine
- Heap leach operations need to be flexible. Ore production rates change and the properties of the ore placed upon the pad vary with time. To optimize head grades to the plant, flexibility in the solution delivery and recovery system is essential. Tying the system to one specific leaching plan limits the mine's potential for economic success
- Simple designs are the best. As with any engineered facility, simplicity makes the system less likely to experience problems. Automation within a SX/EW plant, where controls are within close proximity of the equipment, function well and aid operators with their job. However, on a heap leach pad, where all is exposed to the elements, simple designs that are easy to monitor and repair work best
- Quality control during and after construction is very important. Several problems requiring repairs and/or operation changes might have been avoided through careful quality control during the construction phase, and perhaps more importantly, careful management of the facility should continue after construction and after QA/QC personnel have left site.

Conclusions

The discussions with the operators of the heap leach facilities, and experience of the authors in designing and constructing them has led to the following conclusions

- First and foremost, the heap should be designed based on site-specific conditions. Processing plants can be copied and the basic design repeated from site to site, but care must be taken when doing this with a heap leach pad. The topography, the soil, drain materials and ores all vary from site to site.
- Designs should be flexible. Solution delivery and collection systems should not be tied down to a particular system. Designs should be developed considering future expansions/alterations, such as allowing room for additional pipes, pumps, ponds and trenches. Designs should also be developed to allow flexibility should the ore types change enough to alter the leaching cycles and/or quantities.
- Special care is needed when designing a drainage layer. If economically feasible, the drain material should be designed to act as a filter for the ore and should be resistant to chemical breakdown. If placing a complete drainage blanket is not feasible, the area around the collection pipes should be protected. Select gravel and/or geotextiles have worked at several sites.
- Money spent on quality pipes is money well spent. Acid resistant materials should be used for all parts of the pipe network, including couplers, ties and fasteners. Manufactured couplers are the best. Several pipes have pulled apart beneath heaps where improper couplings have been used. If pipes clog and delay inventory, revenue is lost that is hard to make up, especially if the process facility continually runs at maximum output.
- Doubling the amount of small collection pipework within the pad is a relatively low cost way of increasing the rate at which the solution is recovered from the pad, decreasing the amount of inventory within the heap, especially if quality drainage material is difficult to obtain.
- Inter-lift liners can be advantageous if designed properly as they decrease the time the solution spends in the heap and can speed up copper recovery. However, studies are required to determine the value of residual copper below the inter-lift liner and what effects this has on the economics of the operation.

Acknowledgements

In addition to the individuals thanked for their contributions to the original paper:

- Dave Newhook, Process Superintendent, Lomas Bayas Mine
- Yerko Yutronic Flores, Crushing and Leaching Area Foreman, Lomas Bayas Mine
- Günther Ahlborn Klein, Chief Plant Engineer, Quebrada Blanca Mine
- Ricardo Alvarado, Plant Operations Chief, El Tesoro Mine
- Percy Mayta, Leach Superintendent, El Abra Mine
- Marlon Bruna Ponce, Senior Metallurgist Oxide Plant, Escondida Mine
- Roberto Jamett Sisnec, Engineering Manager, Knight Piésold S.A.
- Lorena Rivas of Knight Piésold S.A. for her time in organizing the site visits.

The authors would also like to thank Carl Burkhalter who compiled a considerable part of the original paper.

Reference

BURKHALTER, C., ANDRADE, H., and GARDNER, T. 'Copper Heap Leach Pad Performance: Geotechnical Lessons Learned, Evaluation of Several Heaps After Three Plus Years of Service', 2002. SME Preprint Number 02-161. ◆