# THE DEVELOPMENT OF NICKEL LATERITE HEAP LEACH PROJECTS

By

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## 1. INTRODUCTION

Owing to the potential for comparatively low capital costs and lower economic cut-off ore grades, heap leaching has been proposed as an alternative processing route for the processing of nickel laterites by a number of recent projects, including European Nickel's Çaldağ project in Turkey and Acoje project in the Philippines, Vale's Piauí Project in Brazil and Metallica Minerals' Nornico project in Australia, among others. Indeed, most new nickel projects are investigating heap leaching as an option for at least a portion of the production.

On the surface, heap leaching of a nickel laterite would not appear to be attractive owing to the low permeability of most nickel laterite ores, coupled with the expected high acid consumption and long leach cycles. The concept of heap leaching of nickel laterites was firstly proposed by Agnatnizi-Leaonardou and Demaki[1], who achieved over 80% nickel recovery during column leach tests conducted on Greek laterite samples. More extensive development work on heap leaching and metal recovery from solution was undertaken by BHP Billiton, who applied acid agglomeration to a range of nickel laterite ores, including limonites, saprolites and fine clay bearing ores[9]. They also introduced the concept of two-stage heap leaching, using a lead and a lag heap. An important observation was made in column testing in that by controlling the acidity of leachate solutions, nickel could be preferentially leached over other major gangue elements, especially iron-containing minerals. This observation has been reinforced in more recent project investigations including the Çaldağ and Nornico projects. The observation that nickel-bearing minerals often leach at faster kinetics than iron-bearing gangue means that acid usage is generally lower than more omnivorous processes, such as atmospheric leaching in tanks.

Since 2005, Vector Engineering, Inc. (now part of the Ausenco group of companies) has been involved in the development of a number of nickel laterite heap leach projects around the world, initially in terms of geotechnical design and development, and more recently process design, PLS recovery and environmental integration. These projects include current nickel laterite projects under development such as Çaldağ, Acoje, Piauí and a number of other project investigations in Central and South America, Indonesia, the Philippines and the USA. The impetus for the design of heap leaching in these projects has been from experience developed over many years of copper and gold heap leaching; however, nickel laterite projects involve unique issues which need to be considered in project development. The current paper discusses some of these issues, particularly the integration of geotechnical, PLS processing, water management and environmental issues.

## 2. KEY ISSUES IN A NICKEL LATERITE HEAP LEACH PROJECTS

In consideration of nickel laterite heap leaching there are generally several major questions which need to be addressed, some of which are generic, and some project specific. Based on recent experience some of the main issues to be addressed are:

### Geotechnical Issues

- Heap permeability, which affects not only the height of heap, but also the mode of operation and cycle time, and how permeability changes with time.
- Method of heap construction and (for a dynamic heap) off-loading.
- Residue or tailings management – not only of spent leach ore (generally 'ripios' in South America and that term has been adopted here), but also process plant residues which can be similar in volume.
- High rainfall effects and the application of "raincoats".
- Physical stability of the heap & residue or residue storage facility (RSF), including slope stability, erosion, and traffic support.

**Processing Issues**

- Heap leach sizing and scale-up.
- Nickel (and cobalt) recovery from pregnant leach solution (PLS) to achieve high quality product.
- Iron Control.
- Magnesium Control.
- Acid Consumption.

**Water Management**

- High rainfall management
- Water supply & surplus water issues

**Environmental Issues**

- Liquid effluent control
- Ripios (spent ore) and RSF run-off
- Ripios and RSF post-closure stability
- Containment systems and covers for the leach pad and RSF

Depending on project specifics, each of these issues needs to be addressed in the project development program, with some being more critical for particular project scenarios. For example, high rainfall management is a critical issue for tropical, inland projects where the discharge of sulphate-containing effluent is generally not allowable.

The following section discusses nickel laterite heap leach project development relating to these issues.

## 3. NICKEL LATERITE PROJECT DEVELOPMENT ISSUES

### 3.1. GEOTECHNICAL ISSUES

**Heap Permeability**

Maximum sustainable irrigation rates are directly related to permeability. Thus, a key issue applicable to all laterite and saprolite deposits is the low permeability of the ore and its sensitivity to heap height. With nickel laterites this is further complicated by dissolution of up to 30% of the solids and the related destruction of the permeability-enhancing agglomerates. Therefore, ore permeability testing should include both fresh agglomerate and leached residues or ripios (representing the lowest permeability) over a range of simulated heap or lift heights. In several recent testing programs including column metallurgical tests followed by geotechnical analyses, ripios samples reported permeability values consistent with sustainable irrigation rates of 5 to 10 L/m$^2$/hr with maximum lift heights of 4 to 8 m. Higher irrigation rates or thicker lifts would have resulted in fully saturated heaps, surface ponding, slope instability and high susceptibility to liquefaction (both earthquake induced and static). Within these ranges of lift thicknesses and irrigation rates, unsaturated permeability testing generally suggested a high degree of saturation by the end of the leach cycle, which also affects slope stability and liquefaction potential. These data further suggest that multi-stack heap drainage would be significantly impaired, thus indicating the need for thin liners and drainage systems between each lift, as is common in oxide copper heap leaching[15].

For steady-state irrigation under assumed fully saturated conditions (as a limiting condition), the following Table 3.1 indicates the maximum possible irrigation rate as a function of saturated permeability. For practical purposes the allowable irrigation rate would be much lower – one third to one fifth would be a typical range – of these values to provide for variations across the heap and to avoid an unacceptably high degree of saturation.

**Table 3.1: Maximum irrigation rates as a function of saturated permeability (fully saturated lift)**

| Permeability, Saturated (cm/s) | Maximum Irrigation Rate (L/m$^2$/hr) |
|---|---|
| $1 \times 10^{-3}$ | 36 |
| $5 \times 10^{-4}$ | 18 |
| $3 \times 10^{-4}$ | 10 |
| $1 \times 10^{-4}$ | 5 |
| $5 \times 10^{-5}$ | 2 |

A key point in interpreting metallurgical column leach data in terms of permeability has been that small columns generally are optimistic in terms of drainage properties. This is caused by a number of factors, ranging from lower ore densities to bridging along the column walls to solution channelling. In one case a sample was leached in a small (nominally 200 mm) diameter clear plastic column. The laboratory reported sustainable irrigation rates of up to 100 L/m$^3$/hr though the ore was a limonite. Visual inspection of the column showed that most of the solution had followed channels along the column-ore interface (Figure 3.1). Larger columns (say around 1,000 mm diameter), properly loaded, tend to report more realistic drainage information and there is good correlation between performance in these columns, geotechnical testing and actual heap performance.

**Figure 3.1 Channelling in a small diameter column**

Key factors that affect permeability and thus heap drainage are:

- Physical properties of the ore, including: particle size distribution; clay content and clay mineral type; density and porosity; degree of saturation; and segregation of the stacked ore. Most of these change for the worse with time in an acid leach environment.

- Agglomeration: principally influencing drainage and acid distribution early in the leach cycle, as the agglomerates tend to fully degrade during leaching. Also, agglomerated ore tends to segregate less during stacking and thus will channel less even after the agglomerates have degraded.

- Method of heap stacking (trucks, stackers working in advance or retreat modes) which affects as-stacked density, segregation and agglomerate quality.

- Segregation in the heap (see Figure 3.2), which can create zones of lower and higher permeability, and the solution will preferentially flow though the high permeability zones, starving the other areas for acid, as well as destabilizing slopes.

**Figure 3.2 Segregation and solution channeling in a lateritic heap trigger a large slope failure**

- Degree of saturation: the permeability increases as the saturation level approaches 100%. Most geotechnical laboratory data is based on 100% saturation (or very close thereto), but in operations initial conditions will be much lower (thus sometimes limiting the start-up irrigation rate for fresh ore) and some variation across the heap is expected. Further and very importantly, heaps should not be designed to operate fully saturated, but rather saturation should be limited to a thin zone at the base of the heap. Thus, both conventional saturated and unsaturated permeability testing should be conducted and used in the heap modelling.

- Lift thickness: ore compresses with load which reduces the permeability, and the matrix can collapse with sufficient load which can drastically reduce permeability. Figure 3.3 demonstrates the typical permeability response with increasing load for a range of laterite ores.

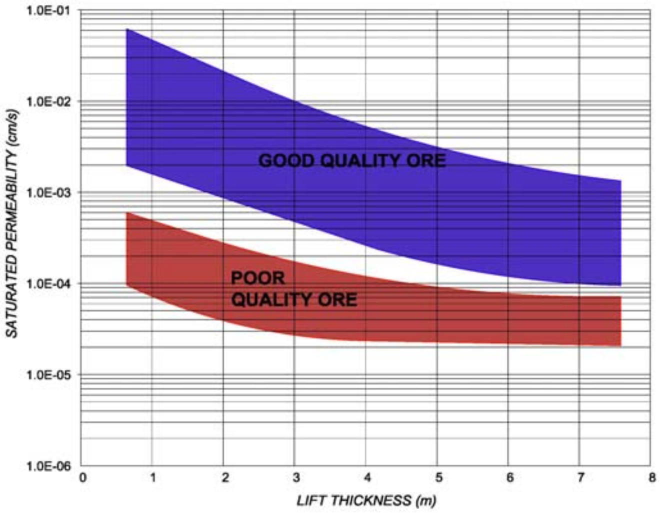

**Figure 3.3 Permeability vs. Lift Thickness by Laterite Ore Quality**

**Heap Construction and Off-Loading**

Either multi-stacking (conventional, permanent heap) and dynamic heap (on/off leach pad) are appropriate for nickel laterites, depending on site and ore factors. For several project trade-off studies both multi-stacking and dynamic heaps were found to have similar initial capital costs and similar life-of-project NPVs. Thus, the decision between these two technologies will often be driven by factors other than economics. Generally speaking, the relative advantages of each approach can be summarized as:

- Leach cycles: short, well defined leach cycles tend to favour dynamic heaps while longer or variable cycles favour multi-stacking.
- Land availability: dynamic heaps require more total land because of the ripios disposal, but multi-stacking requires more area for the initial operation and larger "flat" areas.
- Ripios disposal and dump closure costs: a combined dump (with ripios from a dynamic heap and plant residue) can be smaller and thus less expensive to close than two separate piles (a conventional heap separate from a residue disposal area);
- Ability to leach the spent ore (a ripios leach facility) to recover additional metal should be considered. For most nickel laterites, however, the ripios will be of such poor drainage quality that additional leaching will probably not be practical.
- Water balance: because a dynamic heap requires a larger total area (heap plus ripios dump), but the water from the ripios dump can be easier to divert from process than from a larger multi-stack heap.
- Traffic support capacity of leached ore: supporting the stacker over the prior lifts of leached ore is a key limitation for a multi-stack system with lateritic ore.
- Risk factors can vary considerable between the two approaches, and it is often a risk analysis that leads to the final selection

For both multi-stack and dynamic heaps, there are four approaches to stacking the heap:

- Retreat stacking of the leach heap with a conventional radial stacker. Lifts of 2 to 10m can be accommodated with conventional radial stackers (see Figure 3.4).
  - Applicable to either multi-stack or dynamic.
  - Most common method for small and medium size copper operations
  - In use at: Tintaya (Cu, Peru), Cerro Verde (Cu, Peru), and many others.
- Advance stacking using trucks to dump the ore on the active life.
  - Common in gold and silver heap leaching where the quality of the ore is generally very good, and in thick lift, high tonnage copper dump leaching.
  - Probably not applicable to nickel laterites due to the susceptibility to compaction, agglomerate degradation, etc.
- Advance stacking of the leach heap with a low-height radial stacker (a hybrid system using the simple equipment of the retreat stacker concept but in advance mode). This offers the advantage of not needing to operate the stacking system over the underlying leached ore lift (and thus reducing traffic support issues).
  - Generally only applicable to multi-stacking.
  - Can damage fresh agglomerates and compact the top of the active lift
  - In use at Ocampo (Au, Mexico)
- Advance stacking with a self-propelled tripper-stacker (see Figure 3.5).
  - Suitable for a very broad range of lift thicknesses.
  - Same advantages of advance stacking with a radial stacker, but suitable for higher tonnage rates and generally requires less labour.

**Figure 3.4 Radial Stacker Operating in Retreat Mode, Chile**

**Figure 3.5 Tripper Stacker Operating in Advance Mode, Chile**

Dynamic heap require that the ripios or leached/spent ore be removed after each leach cycle. Ripios off-loading options can be summarized as:

- Loaders or shovels feeding light trucks.
  - Applicable to smaller operations
  - Lower capital but higher operating costs
  - In use at: Tintaya (Cu, Peru)

- Loaders feeding conveyors
  - Not common but may be well suited to some nickel heap leaching.
  - Portable conveyors (e.g., “grasshoppers”) can be used on the pad, feeding an overland conveyor to the ripios dump.

- Reclaimer system (see Figure 3.6)
  - Most common system with larger production rates
  - Economics improve as lift thickness and tonnage rates increase
  - In use at: El Abra (Cu, Chile), Radomiro Tomic (Cu, Chile), Gaby (Cu, Chile)

Figure 3.6 Reclaimer Bucket Wheel, Chile

### Plant Residue Management

Plant residue generally consists of three components: iron precipitates (the largest fraction), sulfates (gypsum, magnesium sulfate), and small quantities of other process sludges, and can be produced in any of these forms:

- Conventional or thickened slurry
- Paste
- Filtering

The disposal or management options thus include:

- Conventional tailings impoundments (slurries or paste)
- In-pit disposal (slurry, paste or filtered tailings)
  - Slurry or paste will require containment berms similar to those required for ex-pit disposal
  - Filtered residue can be dry stacked in the pit and may require little or no structural containment

A number of authors have suggested that dry stacking of filtered tailings in a Residue Storage Facility (RSF) is the preferred method for all sites and all tailings streams when considering stability and environmental containment. Unfortunately, often the cost of producing filter cake is prohibitive. In most of the nickel heap leach operations studied by the authors, residue filtering was elected because of the process benefits (improved metal and acid recovery) and thus dry stacking of the residues was selected for tailings disposal. Since the residues contain very high levels of sulphates and magnesium, low pH and often elevated manganese, an environmental containment system (base liner and drains and closure cap) will often be required unless good geologic containment and suitable climate factors are present. Because the shear strength of the residues will generally be very low and the material is susceptible to liquefaction, some method of stabilizing the final slopes will usually be needed. Analyses have indicated that combinations of small stabilizing buttresses (which have a height a fraction of the ultimate dump height) and compaction of the exterior shell of the dump (with or without the use of fly ash or Portland cement) can achieve good stability as well as erosion protection (and often become part of the closure capping system). While the residue will usually have a low permeability, leachate will be produced by compression of the residue as well as normal leaching actions (especially in wet climates) and thus a system to collect and remove this water would generally be required.

If the process selection does not lead to filtering of the residue, then the tailings management options would broaden to include conventional slurry, thickened slurry and paste, with either all the residue streams comingled or managed separately, and management would be similar to that required for PAL or HPAL residue, with some differences in chemistry and thus environmental containment requirements. However, conventional systems can present a significant long-term risk that should be factored into the analysis (see following section on Physical Stability).

Mine backfilling is often considered in nickel projects and when circumstances allow can be a very good management method. Often either overlooked or underestimated is the complexity of coordinating mine planning with tailings management, and the need for proper containment and closure (either physical or environmental or both) for the tailings whether in- or ex-pit, as well as the complexities brought by high rainfall sites.

## Physical Stability

### *Ripios: Multi-stack Heap or Ripios Dump*

The geotechnical behaviour of laterites is significantly different from other ore types, and this is aggravated by strong acid leaching. Freshly agglomerated nickel laterite ores can have relatively good strength and permeability, but both non-agglomerated and leached agglomerates can have very poor geotechnical properties. Leached ore can also experience significant changes in physical and chemical properties with time and exposure to acid, creating complexities in modelling the behaviour as well as sampling and testing. Shear strength will decrease as the agglomerates degrade and a large fraction (20 to 30%) of the mass of the ore is dissolved. Permeability decreases (often by a factor of 100) due to the same factors and can be aggravated by reprecipitation of iron compounds as is common in two-stage leaching. As the permeability decreases the in-leach ore experiences increasing saturation, which increases the vulnerability to liquefaction. By the end of the leach cycle, which can be longer than one year, the permeability may be sufficiently low that the heap effectively does not drain. This makes either working over the leached lift (in a multi-stack heap) or removing the ripios (in a dynamic heap) complicated in that even after weeks of drainage the ripios can be at over 90% saturation. Tests from several sites indicated that CBR (a common measure of traffic support capacity) can be under 5, which is too weak to support even low ground pressure equipment without some form of ground improvement (e.g., treatment and compaction, addition of a layer of waste rock, use of reinforcing grids, or a combination of all of these approaches). When placed in a ripios dump the traffic support capacity can be further reduced since any cohesion or fabric retained in the heap is lost, and the act of dumping the ripios can create excess pore pressures, reducing the shear strength and destabilizing the slopes.

### *Residue or Tailings Storage Facility*

Tailings management facilities tends to be one of the higher risk activities in modern mining and a recent survey found 122 modern Tailings Storage Facility (TSF) failures. Of these, 75% were directly related to seepage or poor drainage issues[2], and nickel residue is one of the poorest draining tailings. Recent significant TSF failures include: Omai (Guyana, 1995), Manila Mining (Philippines, 1995 & 1999), El Porco (Bolivia, 1996), Marcopper (Philippines, 1996), Las Frailes (Spain, 1998), Aurul/Baia Mare (Romania, 2000), Remin (Romania, 2000), and Zhen'an Gold (China, 2006).

Nickel leach residues differ from conventional tailings in that they are largely composed of chemical precipitates (principally iron, magnesium and gypsum) rather than ground rock with just traces of chemical residues. Most of the projects studied plan on using filters for the residue to improve metal and acid recovery and thus slurry tailings may not be common in nickel heap leaching. However, even filtered residues can have relatively high degrees of saturation (above 80% has been measured, and for many geotechnical purposes anything above about 85% is effectively fully saturated) and thus have the same problems as the ripios, but because the residue is chemical precipitates, it lacks a granular media (rocks, sand) that creates shear strength and traffic support capacity. These residues also tend to have much lower permeabilities than ripios, with bench scale and pilot plant residues reporting as low as $1 \times 10^{-7}$ cm/s, a value commonly specified for compacted clay liners. This makes the residue dumps highly prone to liquefaction in that the pore water cannot drain even under relatively slow loading conditions. In addition to having poor slope stability and very poor drainage properties, the residue can be prone to erosion.

Laboratory testing and limited field test pads have indicated that the addition of either Portland cement or pozzolanic fly ash can significantly improve the geotechnical characteristics of residues.

In one example the CBR was increased from less than 2 (untreated) to 13 with 1% Portland cement (by dry weight). Cohesion will also increase which reduces susceptibility to liquefaction, and by increasing the Proctor optimum moisture content can also make the residue more workable (operators will report, for example, that fly ash will “dry back” the residue but it’s really increasing the optimum moisture content and thus causing the residue to behave as if it were drier). Dry-stack tailings or residue dumps will be limited in the allowable rate of rise (e.g., the maximum crest rise, in meters per year, allowable without inducing static liquefaction) due to creation of excess pore pressure and the potential for liquefaction and flow-slide failures. This will generally be on the order of a few to perhaps 10 or 15 m per year. The allowable rate of rise directly controls the area required for active tailings disposal, which affects capital expenses, water management (larger areas cost more and take in more rainwater) and closure costs.

## High Rainfall and Raincoats

Most nickel laterites outside of Australia are found in tropical or sub-tropical climates characterized by both very high annual precipitation and intense peak storm events. This is not unique to nickel laterites, however, and a number of successful heap leach projects have been conducted in high rainfall climates, including: Panama, Myanmar, Ghana, Costa Rica, Peru, Brazil and the Philippines. In such sites the proper management of rain and storm water can be a key driver. One of the techniques almost universally used to manage the high rainfall is the application of temporary geomembrane covers or “raincoats.” More specifically, a raincoat is placed over the heap, ripios or residue dump to shed rainwater from the system before it enters the process circuit. An industry review completed in 2006[10] found 19 heap leach projects that have used or are planning to use raincoats. Among these are current installations at Pierina (Au, Peru), Philex (Au, Philippines) and four projects in planning (two commercial gold plants in Northern Mexico and nickel pilot plants in the Philippines and South America). Raincoats were first used in heap leaching in the late 1980s on gold ore heaps in Costa Rica[13] to allow continuous wet season heap leaching in a very high-rainfall climate. The covers provided several wet season improvements including:

- reduced surplus water and reduced water management issues.
- less dilution of process solutions for improved metal recovery.
- reduced reagent consumption in recirculated solutions.
- reduced likelihood of accidental spills due to excessive storm water accumulation or excessive flows in process solution channels or piping.
- reduced damage to the surface of the heap and ore agglomerates caused by falling raindrops (impact damage) and sheet flow (erosion).

Unlike semi-permanent to permanent covers used in other industries such as landfills, raincoats are generally used for short-term wet-season use, often with dry-season removal to aid in ore placement, irrigation network maintenance, and to encourage evaporation.

## Interlift Liners for Multi-Stack Heaps

Spent ore will continue to consume acid beyond the economic value of the nickel recovered; thus, for the multi-stack leaching it is important to remove the PLS or ILS from the heap once it has leached the active lift. To accomplish this thin liners are placed over each leached lift of ore. These interlift liners generally consist of thin, non-reinforced geomembrane liner placed over the stabilized top of the prior lift. For the retreat stacking mode, the liner is installed as the radial stacker retreats (approximately 5 to 15 m per day depending on the tonnage rate and geometry of the active stacking area). The interlift liner system is advanced and drainage pipes are installed on very close spacing which is becoming the industry standard for copper oxide heap leaching (also to reduce acid consumption) and has been successfully employed at many operations including the Mantoverde copper project in Chile where this technology was first commercialized at large scale. For advance stacking, the interlift liner can be installed ahead of stacking or concurrently, at the operators’ discretion.

An alternative to using a thin geomembranes is to compact the surface of the spent ore, if a sufficiently low permeability can be achieved. This option is currently being studied at one nickel laterite project and the initial data is favourable with compacted spent ore reporting permeabilities of less than $1 \times 10^{-6}$ cm/s. This would reduce operating costs slightly and, more importantly, simplify operations and reduce potential conflicts between the liner installation crew and the conveyor operations. However, compacting the ore in wet periods may not be practical.

### Temperature Effects on Liner and Drainage Pipes

Most leach pad liners and essentially all drainage pipes are made of polyethylene (PE), which is a thermoplastic. As such, its physical properties can change significantly with temperature. Computer simulations on large copper sulphide heaps predict sustained temperatures of 40 to 50°C at the base of the heap. Anecdotal information from nickel laterite pilot plants suggests temperatures of over 70°C can be achieved. Limited laboratory data is available on the temperature effects on geomembrane puncturing (see Figure 3.7). Better information is available for drainage pipe performance, such as presented in Table 3.2, which presents modelling results calibrated with laboratory data. While laterite lifts tend to be thin, the overall height of a multi-stack heap or the ripios/residue dump can exceed 100 m. Note that PE pipes generally collapse at around 25% deflection [14,15]. In both cases the data suggest that temperature should be considered in design.

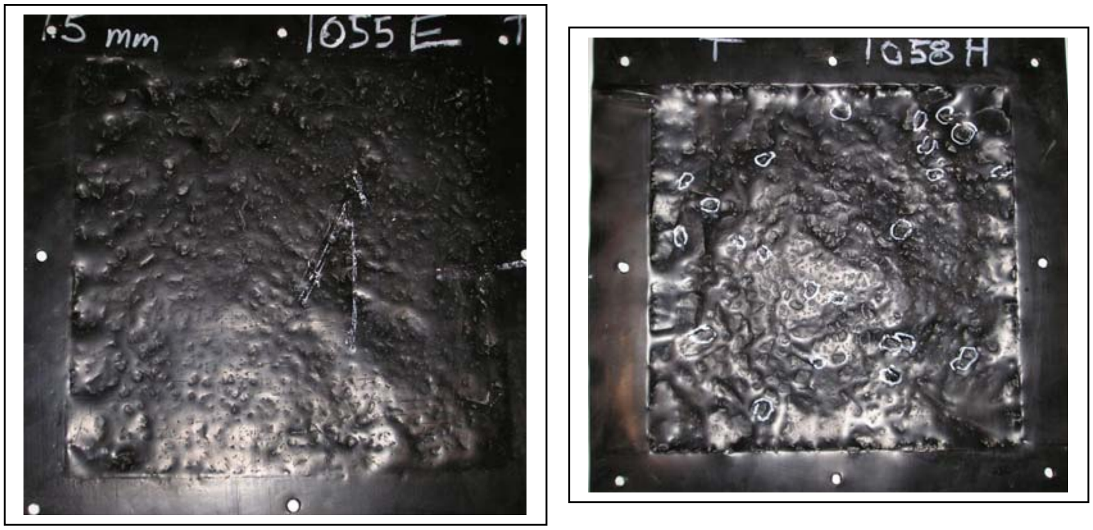

**Figure 3.7 1.5mm thick LLDPE[1] tested for puncture at 120m simulated heap depth at (1055E) 23°C and (1058H) 60°C (white circles indicate failures)**

**Table 3.2: Vertical Pipe Deflection for Dual-wall 150 mm Nominal Diameter Corrugated HDPE[2] Pipe (as % of initial diameter)**

| Heap Height (m) | Pipe Deflection @ 23°C (%) | Pipe Deflection @ 50°C (%) |
|---|---|---|
| 20 | 5.0 | 8.0 |
| 60 | 11.6 | 17.6 |
| 100 | 16.8 | 24.9 |
| 140 | 21.4 | 31 |

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[1] LLDPE: Linear Low Density Polyethylene; HDPE: High Density Polyethylene
[2] HDPE: High Density Polyethylene

## 3.2. PROCESSING ISSUES

### General

Processing issues are critical in a nickel laterite heap leach project because of the high gangue uptake per unit of nickel leached. Typically between 20 and 30% of the ore is dissolved to achieve a nickel recovery in the range 65 to 75%, as compared with 1 to 3% in a typical copper heap leaching project. The comparatively high acid consumption in a nickel laterite project has the following consequences:

(1) High acid usage. For a 1.3% Ni head grade, with 65% nickel recovery to product and an acid consumption of 500 kg/tonne of ore, the acid usage becomes about 60 kgs acid per tonne of recovered nickel.

(2) Leach kinetics become critical. Longer leach times not only increase heap leach size, but can affect the acid usage, as gangue continues consuming acid. There is often an optimum leach time balancing nickel recovery and acid usage.

(3) Heap leach PLS processing needs to be carefully considered owing to the large amount of gangue leached alongside with nickel and cobalt, especially iron and magnesium uptake.

Therefore, although many of the techniques and methods developed for copper heap leaching can be applied to nickel laterites, there are significant differences which must be considered in the process design.

### Critical Heap Leach Process Data

The critical heap leach data required for sizing and ramp-up are:

(1) An understanding of acid consumption versus metal (including impurity) uptake.

(2) An understanding of the impact of agglomeration on heap leach performance and the optimum agglomeration method.

(3) Leach kinetics for nickel/cobalt and key impurities.

(4) Development of the most appropriate heap leach cycle, for example, the extent of recycle needed to increase nickel tenors in the PLS.

(5) An understanding of scale-up issues in nickel laterite heap leaching.

(6) An understanding of the variability in heap leaching behaviour for different parts of the orebody, especially if there are significant variations in mineralogy.

These data need to be generated from both column and pilot scale test heaps, as nickel laterite heap leaching is relatively new, and scale-up issues are still being developed. Illustrations of an operating test heap from the Çaldağ Nickel Project are given in Figure 3.8[10].

**Figure 3.8: Çaldağ Pilot Test Heap during Operation**

Figures 3.9 and 3.10 present the key heap leach process results from a nickel laterite heap leach project under development. The illustrated response is typical of many nickel laterite projects, and indicates why heap leaching has become a potential low cost alternative for many nickel laterite projects. Metal recovery versus acid usage data (Figure 3.9) shows that nickel and cobalt containing minerals are leaching preferentially to the bulk magnesium silicate and iron oxide containing gangue. However, there is an optimum nickel extraction, above which additional acid addition is largely being used to consume more gangue with diminishing nickel recovery. The order of metal recovery is cobalt > nickel > magnesium silicate minerals > iron oxides (largely goethite).

Figure 3.10 presents the leach rate data for test columns and a corresponding test heap (recovery versus flux), which provides the basis for commercial heap leach sizing and leach cycle development. This data is indicating that there was a reasonably good correlation between column and test heap results, particularly when sample variability is considered. Other projects, such as Metallica Minerals pilot scale tests conducted on samples of Bell Creek North ore, have shown similar results. Such scale-up data is considered to be critical for current nickel laterite heap leach projects until a better understanding of process scale-up issues are developed in projects. The columns and test heaps also allow a range of geotechnical data to be determined (as previously discussed). For example, only at test heap scale can trafficability and compaction issues be properly assessed, which are critical for a decision of multi-stacking versus dynamic heap leaching. As heap height and lift thickness are critical design parameters, not only affecting permeability (refer to Table 3.1), but also leaching rates, column and test heap data needs to be generated at heap heights similar to that expected in the commercial plant. For current nickel laterite projects, the expected range is 3 to 8 m. For this reason it is considered that small scale testing (say with 1 m high columns) cannot be employed for design criteria development of projects.

The leach rate data also provides valuable input into the design of the heap leaching circuit. For example, with slow leaching ores, recycle of intermediate leach solution (ILS) can be employed to improve nickel and cobalt tenors in the final PLS. The high levels of impurities present in the PLS limits the extent of recycle possible.

## Nickel and Cobalt Recovery from PLS

A range of processing options are being developed for nickel and cobalt recovery from heap leach PLS, many of which have been discussed in Willis[20]. These options include:

- Mixed Hydroxide Precipitation (MHP)
- Mixed Sulphide Precipitation (MSP)
- Ion Exchange (IX) Options using a range of nickel and cobalt resins (including Lewatit TP207 from Lanxess, Dowex 4195 from Dow Chemicals, WP-2 from PSI, and MRT Superlig®).

The PLS generated from nickel laterite heap leaching differs from pressure leach discharge liquor (where most current nickel recovery routes have been developed) owing to the high iron and aluminium-to-nickel ratios present in solution. A typical nickel laterite heap leach PLS can contain 2-4 g/L Ni, 15-30 g/L Fe, 2-5 g/L Al and 20-40 g/L Mg. The relatively high impurity levels can result in substantial nickel and cobalt losses during iron precipitation, often 15-20%, which is difficult to recover. This is particularly a problem if a high purity MHP product is required for further processing in a “QNi’ type circuit where the MHP product has tight iron and aluminium specifications. Although ferric iron can be precipitated in the pH range 2.5 to 3.5, aluminium requires a pH of 4-5, and ferrous iron a pH of 4-5.5 (with oxidation to ferric iron). The nickel and cobalt co-precipitation losses at these pH levels are substantial.

Options for reducing nickel co-precipitation losses are:

- Two stage iron precipitation circuits.
- The use of IX based systems for selective nickel extraction, especially from ferrous iron and aluminium.
- Considering an MSP type product where aluminium and ferrous iron removal are not required prior to the production of a nickel/cobalt containing product.

In addition to nickel and cobalt losses during iron precipitation, solid / liquid separation issues also need consideration, especially iron residue thickening and filtration (assuming iron residue is to be handled by dry stacking). The relatively high iron and aluminium levels in solution mean that solid / liquid separation of iron residue needs to be carefully considered to avoid this area being a bottleneck in processing. Some options to be considered to improve iron residue solids handling include:

- Operation of iron precipitation at elevated temperatures to produce goethite or para-goethite.
- The use of seed recycle to improve the degree of compaction of iron residue, and therefore its physical handling properties.
- Careful evaluation of flocculants and coagulants during the evaluation program.
- Selection of the most appropriate iron residue filtration system, particularly minimizing soluble nickel losses to the iron residue. The iron residue washing circuit design can have a significant impact on the overall water balance, therefore needs careful attention.

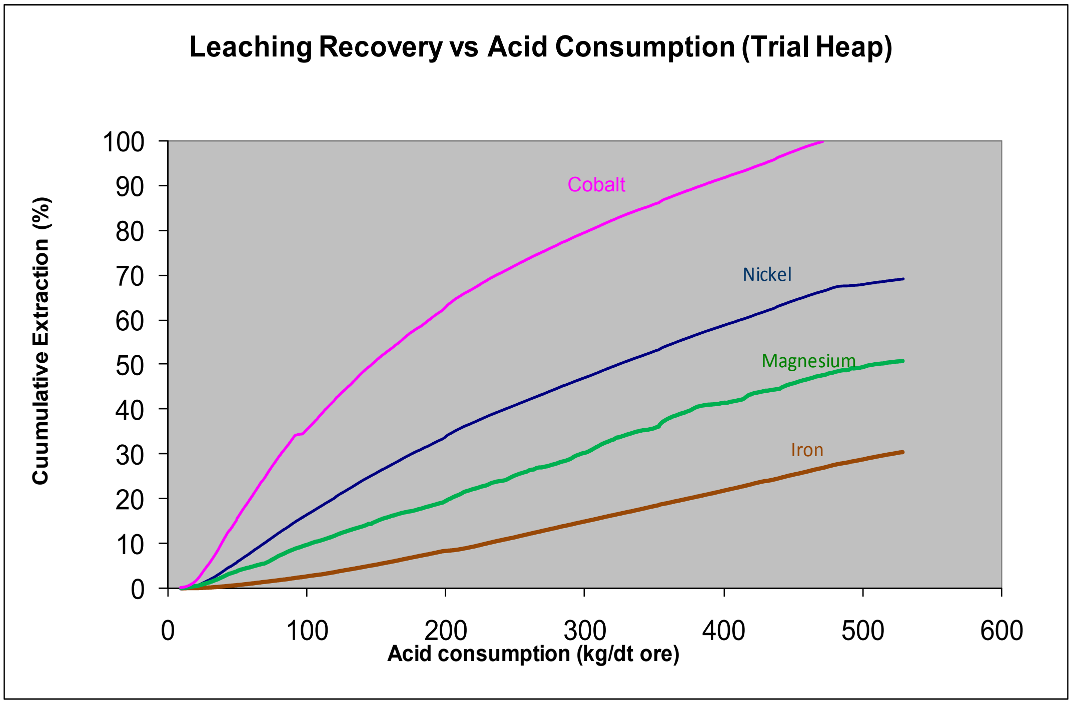

**Figure 3.9: Example of Key Metallurgical Data generated from a Nickel Laterite Heap Leach Development Program – Extraction versus Acid Usage**

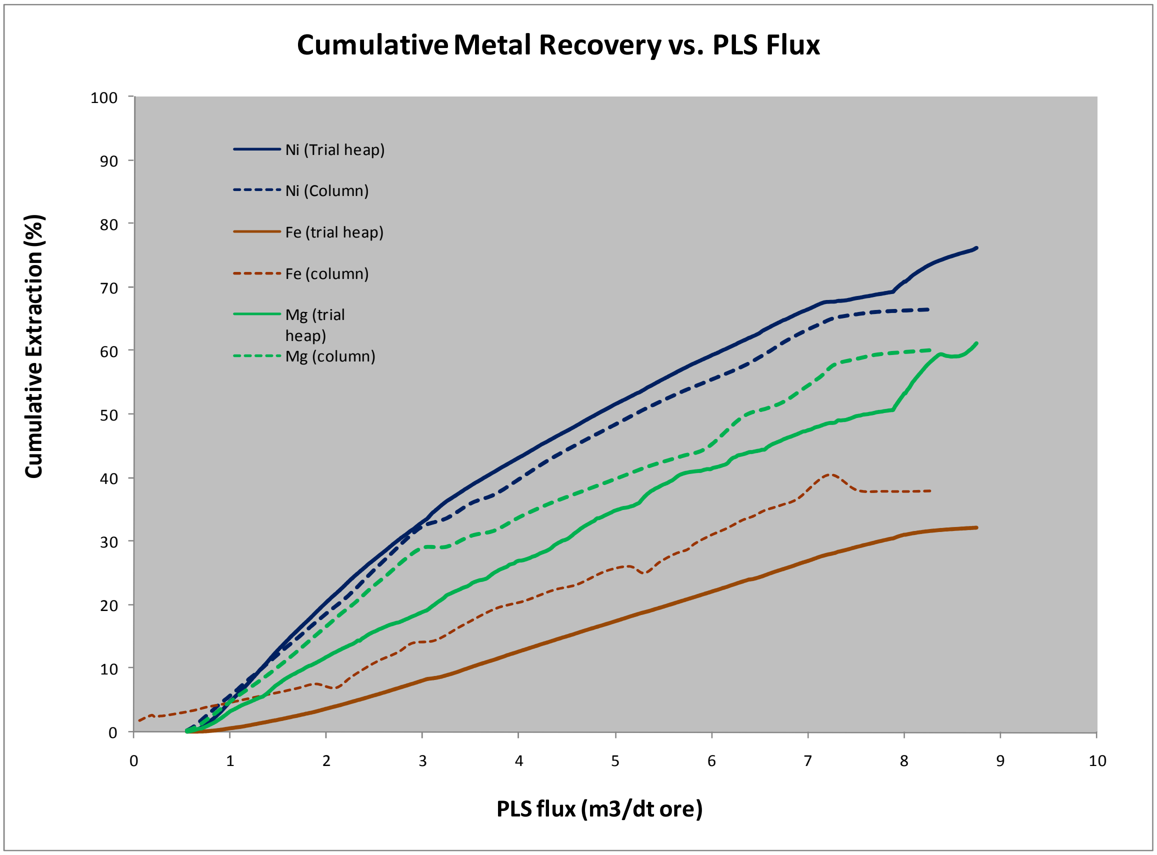

**Figure 3.10: Example of Key Metallurgical Data generated from a Nickel Laterite Heap Leach Development Program – Leach Kinetics**

A second area to consider is the type of nickel/cobalt product. As many nickel laterite heap leach projects are being considered at the 10-30 ktpa range of nickel production, full value adding to nickel metal can be difficult to justify, both in terms of circuit complexity and capital costs (i.e. the reason for nickel laterite heap leaching is often to develop a low capital cost, low complexity project). Intermediate products then become the preferred product, but this requires a market for the product. Although more complex to produce, an MSP product may generally be preferable to an MHP as it is more ‘marketable’ as an intermediate product, especially as a ‘QNi type’ MHP is difficult to produce to the required specifications.

### Manganese and Magnesium Control

The heap leaching of nickel laterites results in significant amounts of magnesium and manganese sulphate being dissolved into solution, which needs to be handled in the overall process flowsheet. This has two consequences – firstly soluble magnesium and manganese must be disposed of in the process circuit, and secondly high soluble levels of magnesium can impact on heap leach performance , therefore concentration levels must be maintained below levels which would adversely affect heap leaching (such as double salt precipitation in the heap).

Magnesium sulphate control is closely linked to water management. For dry climates, evaporation ponds can be employed, however even here the water balance can be an issue owing to reduced evaporation rates from saline containing solutions. For wet climates (with a net negative evaporation rate), the issue is more serious as evaporation ponds cannot be employed. In projects close to the coast, ocean disposal of neutralised effluent is an option, subject to environmental restrictions. This generally means controlling manganese to discharge levels in the range 1-10 mg/L, and producing an ocean discharge of similar composition to that of the surrounding ocean. For inland projects in wet climates, the problem of magnesium sulphate disposal is substantial, as even fully neutralised liquor will not generally meet World Bank standards for sulphate disposal in fresh water systems.

Vector has been involved in several tropical inland projects where sulphate containing effluent disposal is not possible. Some strategies being considered for these projects are:

- Rain covers on the heap leach to minimize rainfall ingress.
- Continuous sealing and capping of residue dumps to minimize sulphate-containing seepage.
- Adequate bleed neutralisation capacity within the process circuit.
- A good understanding of ‘dry’ and ‘wet’ water balance conditions to both ensure adequate water supply (dry conditions) and effluent treatment (wet conditions).

## 3.3. WATER MANAGEMENT ISSUES

### Overall Water Management

Outside of critical geotechnical issues, water management is likely to be the most critical issue in nickel laterite project development. Although water management issues are project specific, for nickel laterite heap leaching the following will generally need to be considered:

- Water supply issues, even in wet climatic conditions.
- High rainfall management.
- Water balance and effluent disposal.
- Emergency pond sizing.
- Water storage pond sizing.
- The interaction between process and emergency ponds to minimize dilution of process solutions.

Figure 3.11 presents an overall schematic of water management within a nickel laterite heap leach project. The key water inputs and outputs are:

**Inputs:**

- Water associated with feed ore.
- Fresh water requirements for process plant
- Ripios / Residue Storage Facility (RSF) return liquor
- Rainfall feeding heap leach and ponds
- Run-off from heap leach (particularly covered heaps) and process plant

**Outputs:**

- Water associated with ripios and RSF discharge
- Water in product
- Evaporation losses
- Excess neutralised liquor to either evaporation ponds (dry weather project only) or effluent disposal (if permitted).

Based on these streams, project water balances can be developed based on different scenarios, in particular ‘dry weather’ conditions which will determine the maximum water demand from the project, and ‘wet weather’ conditions which will determine the potential for excess water generation, and therefore what steps are needed to either control excess water production, or to treat this liquor.

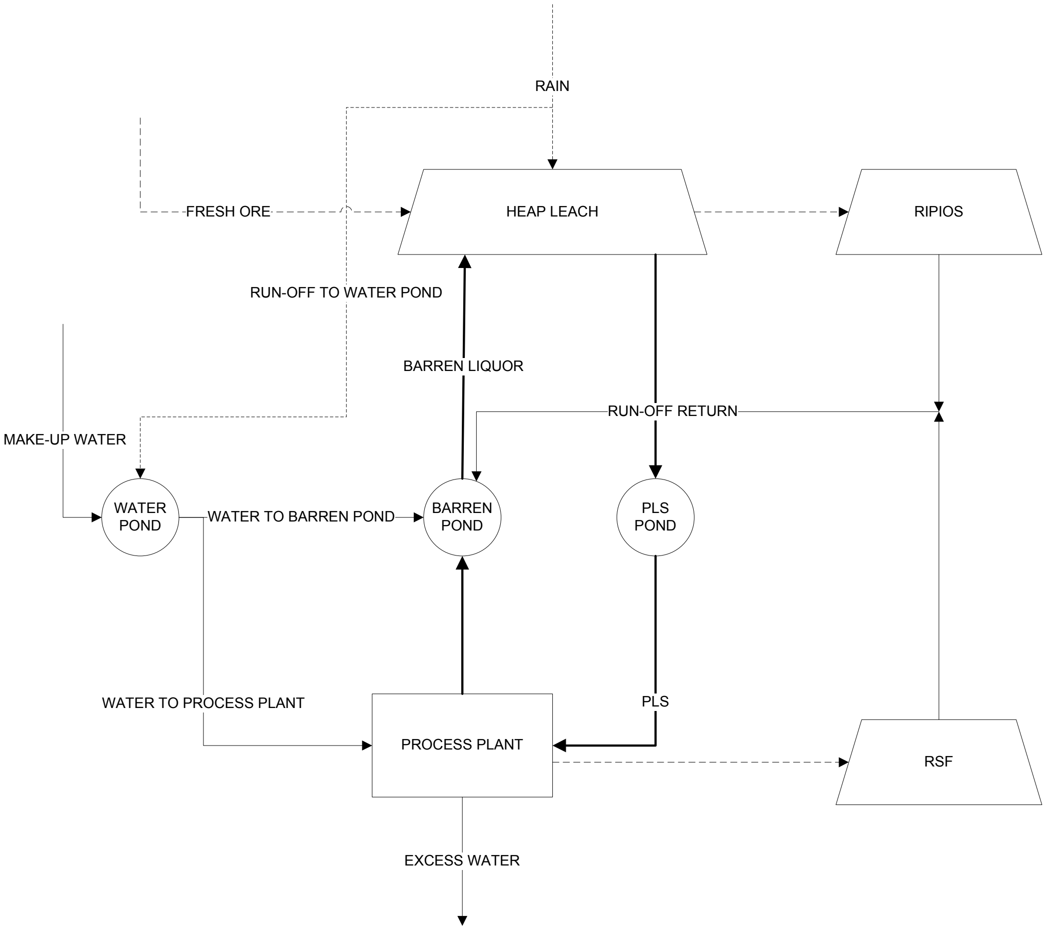

Figure 3.11: Nickel Laterite Heap Leach Water Balance

### High Rainfall Management

High rainfall management is particularly relevant to wet tropical projects, but can be an issue in any weather climates. Tropical laterite projects can experience very high annual rainfall, with average annual precipitations of 2,000 mm to 4,000 mm common. Tropical storms can also be very intense, with peak rainfall of over 200 mm in a few hours. The high annual rainfall presents problems of surplus water, with wet months making some construction activities very difficult or impossible (including operation of the stacking equipment for ore, residue and ripios stacking as well as deploying liners), and the intense storms can damage agglomerates, create zones of channelling within the heap and otherwise impede leaching. To address these various concerns a multi-facetted approach can be integrated into the project, including:

- Raincoats (thin geomembrane liners) to shed rainwater from the heap and dumps, and to protect fresh agglomerates (discussed previously)
- Dual stacker systems for multi-stack heaps, using retreat methods for heap normal operations and advance stacking for the residue dump, all with low ground pressure equipment;
- Heap stacking may need to be discontinued during high rainfall periods (and thus the design should recognize this in the agglomerator and stacker availability);
- Fly-ash or Portland cement stabilization of the external shell of the dumps for both erosion and slope stability (discussed previously);
- Aggressive stabilization of the underlying lift of leached ore in multi-stack operations, using combinations of reinforcing grids, waste rock, and fly-ash or Portland cement stabilization of the ripios.
- Adequate bleed neutralization capacity to prevent effluent disposal.

### Water Supply Issues

Because of varying climatic conditions throughout the year, steady state mass balances cannot be employed for determining maximum project water demand, and water storage requirements. Dynamic water balances of ‘dry’ and ‘wet’ project scenarios can be utilized for this purpose, applying the water balance model illustrated in Figure 3.11. The water balances should consider:

- Peak seasonal storage: Wet cycle (usually 100-year return) net cumulative water gain.
- Dry season water supply: Dry cycle (25- to 100- year return) maximum water demand.

For projects employing heap leach raincoats, surplus run-off water generated from the heap leach (and possible the residue dumps) can produce significant fresh water which can be used for water make-up to the water pond.

If inadequate fresh water is available to meet project water requirements, saline or hypersaline water has been considered as an alternative water supply. The use of saline water would have a substantial affect on project development as it can affect process chemistry as well as materials of construction.

### Emergency Pond Sizing

Emergency pond sizing is critical in nickel laterite heap leach projects owing to the substantial liquid hold-up within a heap. The moisture level in an operating nickel laterite heap is in the range 30-40% depending on the mineralogy of the ore, which is much higher than most comparable copper heap leach projects. Similarly drain-down volumes are higher during power outage conditions, which must be accommodated in the emergency pond. Typical sizing criteria for the emergency pond is:

- Peak storm: 100-year, 24-hour return event.
- Power outage condition: heap drainage without return irrigation for a period of 12 to 48 hours (depending on conditions such as availability of back-up power and replacement pumps).
- Net cumulative water surplus: from a water balance model considering the design wet year (e.g., the 100-year return wet season) which considers both above-average rainfall and below-average evaporation.

## 3.4. ENVIRONMENTAL ISSUES

### Effluent Control

The main issue in effluent control within a nickel laterite heap project is the handling of sulphate-containing effluents. Strategies for handling effluent disposal in different climatic conditions have been previously discussed in Section 3.3 as effluent control is closely associated with magnesium sulphate control. This is because of the substantial magnesium sulphate deportment into solution during heap leaching, which is not removed from solution during nickel recovery, and therefore needs to be treated in the bleed control circuit. Such effluent control strategies need to be considered under the range of weather conditions expected to be experienced in the project including extreme dry cycle (e.g., 100-year dry return period), typical ‘dry cycle’, ‘normal’ or ‘average; operating conditions, ‘wet’ processing conditions (e.g., 100-year wet return period) and peak storm events. To assist in this evaluation the authors have coupled steady state process models of heap leach / metal recovery plants with dynamic water input conditions, particularly rain and evaporation patterns during a simulated ‘wet’ or ‘dry’ years.

The advantage of heap leaching in these climatic conditions is the capacity to recycle solutions within the process circuit. For this reason, heap leaching can be a preferable alternative to pressure acid leaching or atmospheric leaching where sulphate containing effluent disposal is a major challenge.

### Ripios / RSF Run-off Control

The ripios and RSF run-off control system depends on project environmental conditions, with the most attention being needed for high rainfall conditions where water balance issues are critical. In this case, raincoats provide a method for limiting rain ingress into the ripios and RSF, presupposing the use of dry stacking for tailings disposal.

When raincoats are employed most of the runoff will be clean water and thus the management issue is principally one of managing large peak flow rates. However, part of the active face of the heap and dumps will always be exposed to rainfall regardless of raincoat usage, and these uncovered areas will be vulnerable to producing contaminated runoff. The most common and probably most reliable way to manage this water is to allow it to enter the process circuit and size the conveyance and storage components accordingly. This will also increase the fines entering the circuit, but with sufficiently large ponds the water should be satisfactorily clarified before entering the plant.

Raincoats are also not designed to the same standards as “environmental” containments (such as the leach pad liner) and are prone to both routine leakage and partial failure. For water balance modelling some leakage or bypass should be assumed, and the amount depending upon the quality of the raincoats and the degree of management to be used by the operator. The authors have generally used about 20% bypass for a well designed raincoat system. These bypass rates include allowances for localized failures or loss or raincoats (for example, due to wind damage).

For heaps without raincoats two approaches can be used. The inactive areas of a multi-stack heap can be sealed by compacting the surface and then that runoff directed away from the system with routine testing to verify that the water meets discharge standards. The active area of a multi-stack heap and all of a dynamic heap would take the runoff into the process circuit. This will dilute process solutions but in drier climates the water gain may be a benefit.

If a conventional (i.e. slurry based) TSF is to be employed for residue disposal, then the facility will need to be designed to conventional tailings standards including a robust dam and appropriate provisions for water management. For wet climate sites this will include a large spillway and some sort of management of any spilled water which will probably not meet discharge standards. This could result in serious water balance issues, and may mean that a conventional TSF is inappropriate for the project. Raincoats can be considered, but to date these have never been used on a conventional slurry based TSF and would generally be impractical for all but the smallest facilities.

### Containment & Cover Systems

Base liners for the leach pad, ripios dump and residue storage facility (or TSF) will generally need to meet environmental containment standards and thus require a high level of design, good quality construction and a rigorous system of inspection and quality assurance during installation. Conceptually, the liner “system” includes the foundation preparation and bedding layer, sometimes a compacted clay liner component, a geomembrane liner, and a drainage system over the geomembrane. Leak detection and collection may also be included depending on local standards and the level of reliability desired. A number of excellent papers have been published giving design and installation guidance and thus that will not be repeated herein, and interested readers are directed to Breitenbach et al[6,7,8],Thiel el al[18] and Smith et al[12,15,16], among other authors.

Cover or capping systems are not yet common in the mining industry but will likely become more so as environmental standards continue to increase and projects are advanced in increasingly challenging settings. Nickel residues especially are prone to post-closure problems and it is likely that nickel laterite heap leach projects will incorporate some form of closure capping to secure the residues. As with environmental liners, a wealth of information on cap design and construction is available including Breitenbach[4], Smith et al [13,17]. One key feature of nickel residues is the inherently low permeability of the materials, and the ability to enhance this with relatively low cost techniques such as fly ash or cement treatment, allowing the residues or ripios to become part of the capping system.

An aspect of geomembrane technology that is currently subject to rapid advancement is construction quality assurance, especially in the area of defect detection post-installation and the use of geoelectrical methods. A number of recent papers have been published on this technology, speaking to both the technology and the economic and environmental advantages. The readers are directed to Beck, et al[2] and Thiel, et al[19] for more information.

### Post Closure Stabilization of RSF and Ripios Dump

Most mine closure designs are addressing large quantities of relatively stable waste rock or well-contained tailings. For spent nickel leach ore and plant residues, however, the materials are both relatively weak and degrading with time (especially if any residual acidity remains). This poses a challenge for the designer in predicting the long-term physical and chemical properties of the residues. The fact that nickel leach products age is something not well recognized in geotechnical engineering and some (perhaps most) data produced from geotechnical laboratories is not properly connected to the state of the samples tested (that is, the history of their production, the handling and ageing post-production) and this causes some problems in applying that data in the design. Thus, a key point in nickel project closure – both heap leaching as well as more conventional PAL or HPAL – is to properly address this in the geotechnical program.

Beyond sample ageing some of the key closure issues facing nickel laterite heap leaching are (Smith[13,15,16,17], Ramey, et al[11]):

- High rainfall: the need for and long-term performance of closure capping systems including the erosion control components.
- Settlement: heaps, residue dumps and RSFs will be subject to large post-closure settlement which can disrupt drainage courses, affect pipes and other structural components, and rupture the capping system unless conservatively predicted and properly accommodated in the design. Large settlements can also adversely affect slope stability both by changing the slope configuration and by reducing the effectiveness of diversion and drainage systems (and wet slopes are far more likely to fail than dry ones).
- Post-closure maintenance: this will be more important than in an "average" mine due to factors such as climate, the physical and chemical properties of the residues, and often the high seismicity of the sites.
- Effluent management: All of the waste facilities will produce some effluent for some period after closure (e.g. consolidation water from the dumps and heaps) which could continue for several years after cessation of operations and completion of the closure construction. Some facilities, such as conventional slurry TSFs, can produce effluent on a long-term basis.

## 4. INTEGRATION OF DEVELOPMENT ISSUES

The previous section has discussed the main geotechnical, process development, water management and environmental issues which are critical in the development of a nickel laterite heap leach project. Because many of these issues affect other project areas, an integrated project approach is required. This is not always straight-forward, as often different engineering groups or consultants are responsible for separate areas of the project, and there is a decided culture of compartmentalization in mineral project development. By way of example, the following project interactions are illustrated:

### Heap Height

Generally the higher the height of a heap, the lower the permeability in the lower zones and therefore the maximum operating irrigation rate. However, there can be substantial process or operational benefits in operating at a higher heap height (such as reduced operating costs in multi-stacking or residue handling, higher specific nickel extraction rates, or lower impurity uptake); therefore, an optimization between these factors can be required. For this reason, it is recommended that testwork be conducted across the expected operating range of heap heights. Applying geotechnical and process data collected at one heap height to other heap heights can lead to problems, especially if there are substantial differences between project decision and available data. For this reason, heap height and ore variability should be investigated early in a project, particularly as column tests may need to be operated for considerable time (6-9 months in typical) therefore it is difficult to generate new data later in a project.

### Residue Management

Dry stacking of process residue in an RSF is generally the preferred residue disposal option, however, this requires additional capital expenditure in the process plant, and an evaluation of methods for producing handleable iron residue with minimal nickel losses via co-precipitation. Washing of entrained soluble nickel also affects the overall water balance and needs careful design. Similarly a conventional (slurry based) TSF can be considered to reduce processing costs, but may not be possible in high rainfall situations due to its adverse impact on the overall water balance.

### Type of Heap Leach Operation

The mode of operation of the heap leach can affect the overall water balance. For example a dynamic heap can require additional total area, therefore is subject to additional rain ingress when compared with a multi-stack operation. Additionally, a multi-stack operation can lead to additional surplus run-off water generated from the heap leach when compared with a dynamic heap leach, which could be critical in some projects where water supply is a major factor.

### Water Management

All aspects of the project impact on the water balance, especially in high rainfall situations, and need to be carefully considered. Many of these aspects have been discussed during the current paper including stacking systems, the use of raincovers, ripios and TSF disposal, containment systems, processing issues, effluent disposal and dynamic water balance considerations for a project.

These examples highlight the need for a multi-dimensional approach to a nickel laterite heap leach development taking into account geotechnical, metallurgical, water management and environmental issues. Particularly important is the development of the metallurgical and geotechnical testwork program to provide key design criteria. The long timeframes for column and test heap programs generally mean that data collection and evaluation become the rate limiting step within a project, requiring serious planning as it is difficult to generate new information part way through a project.

The current paper particularly highlights the geotechnical and water management issues relevant to high rainfall projects. Strategies are highlighted for the management of high rainfall during heap leaching, ripios and residue disposal and processing of heap leach PLS. The use of dynamic water balance modelling is discussed in overview to evaluate ‘wet’ and ‘dry’ climatic conditions and their impact on a project.

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