

THE ART OF HEAP LEACHING - THE FUNDAMENTALS

L W John

BIOMET Engineering

Abstract

A brief history of percolation leaching and the current technology involved with successful heap leaching is presented. A general orientation of nomenclature, design criteria and commercial applications of percolation leaching is provided. A discussion of why so many heap leach operations have failed which includes a discussion on the failure to fully evaluate or scale up metallurgical testwork for full scale leaching, and a lack of methodology or design in the construction of the heap leach, is given. The fundamentals and rules of thumb in scale up of laboratory testwork results, plant design and heap leach construction are discussed. The very important interrelationship of pH control, percolation and lixiviant consumption is discussed in some detail giving enlightenment as to why many heap leaches give unexplained poor recoveries.

1. Overview of Percolation Leaching

1.1. History

Percolation leaching is by no means a new technology and heap leaching has been documented since at least the mid sixteenth century with other evidence of percolation leaching dating back thousands of years.

The Roman writer Gaius Plinius Secundus (23 - 79 A.D.) wrote about the leaching of copper and the subsequent evaporation of copper sulphate solutions. There are several documentations of percolation leaching over the next 17 centuries including the 190 tpa (Cu) Chiangshan (China) cementation plant which apparently started operation in 1096 and those noted in Agricola's (1556) text *De Re Metallica* less than five centuries latter.



Picture 1. Percolation Leaching Circa 1550, Agricola.

References to large scale heap leaching describing copper extraction from oxide and sulphide copper ores at Rio Tinto appeared from around 1752. The crushed ore was stacked together with timber which was subsequently set alight roasting the sulphides. Water was then percolated through the heap and the resulting copper sulphate solution collected and cementation used to collect the copper.

In 1888, this method of extraction was prohibited by law, due to sulphur dioxide emissions. However the practice of heap leaching without roasting, continued until the 1970's.

It can be safely assumed that where ever percolation leaching was used from ancient times to the present, *Thiobacillus Ferrooxidans* or similar archaea were present, catalysing the oxidation of sulphide minerals. Such microbes capable of assisting heap leaching of metal sulphides were first identified in 1947 in acid mine drainage and in the 1950's and 60's in dump and heap leach solutions.



Woodcut from the book *de re metallica* written by Georgius Agricola (1494 - 1555) illustrating the manual recovery of copper-containing mine effluents which are collected in wooden basins and concentrated in the sun.

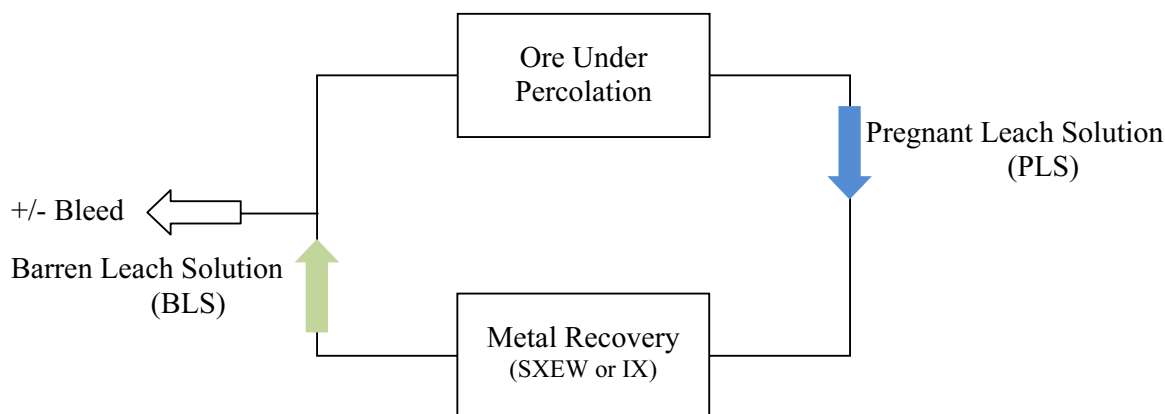
A: gallery
B: wooden vat
C: pool.

Picture 2. Inadvertent In-situ Leaching and Copper Recovery Circa 1550, Agricola.

The first major gold and silver heap leach was the Cortez (USA) heap leach in 1969 which is still operating and was expanded to 63,000 tpd in 2002.

1.2. Fundamental Cycle

The simplest flow diagram of a percolation leach system is one in which the leachate solution, after metal recovery, is recycled back to the leach. Regardless of the type of percolation leaching or metallurgical extraction, this is a fundamental aspect of percolation leaching which hasn't changed in several millennia.



The reason for this recycle of spent or barren solutions back to the percolation of ore is that it is economically important to conserve lixiviant and metals. In most cases the conservation of water is also an important issue.

Metals are rarely fully recovered in the metal extraction process and together with residual lixivants still represent a significant value. Early copper leach operations unknowingly relied on the archaea microbes to produce sulphuric acid and thus the acidic barren solution was recycled as it was

obviously beneficial to the leach. In doing so they inadvertently assisted the iron and sulphur oxidizing microbe populations to build up and thus those operations unknowingly became the first examples of commercial bioleaching.

In modern copper recovery via SXEW the copper is extracted and replaced with hydrogen ions resulting in a drop in pH in the Raffinate. This is a critical aspect of SXEW leach operations in that the acid generated in EW is recycled back to the percolation leach via SX.

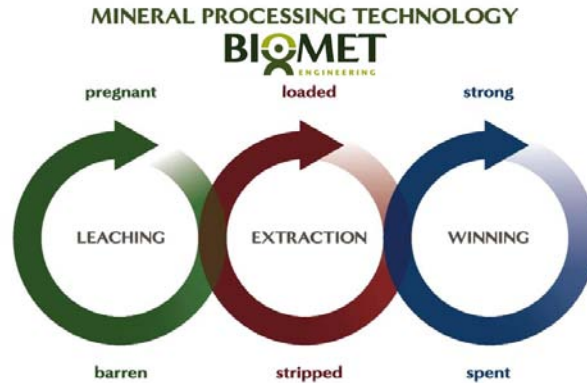
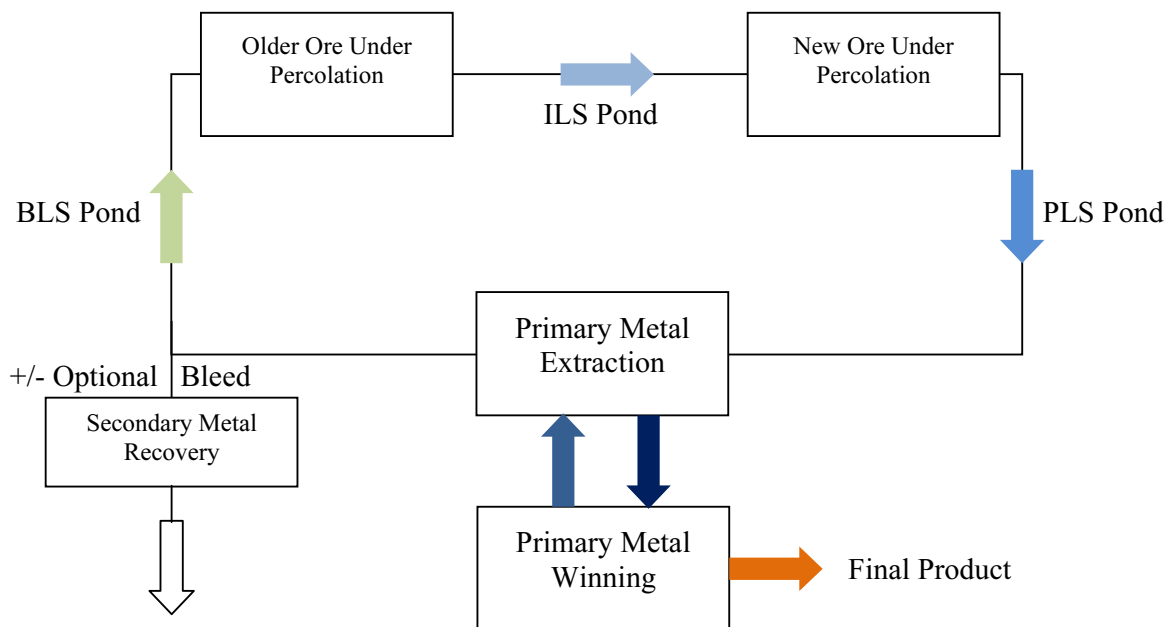


Figure 3 The Process Cycles Common to all Forms of Percolation Leaching

1.3. Nomenclature

Percolation leaching and in particular, heap leaching has a range of unique names and acronyms describing the various aspect of the technology. There has been some attempt by engineers to keep the nomenclature internationally consistent. The following is a simple schematic of a typical modern percolation leach.



1.3.1. Common Nomenclature

Abbreviations, names and acronyms used in percolation and more specifically heap leaching:

PLS	Pregnant Leach Solution
ILS	Intermediate Leach Solution
BLS	Barren Leach Solution
RAF	Raffinate – BLS post SX – a specific term for SX
Extraction	Selective recovery of metals via IX (ion exchange resin or activated carbon) or SX (solvent extraction)
Winning	EW (Electrowinning) or selective ppt ⁿ of metals from extraction eluates or strip solutions
SXEW	Solvent Extraction followed by Electrowinning – predominantly Cu but also Zn, Co & Ni
SXPPT ^N	Solvent extraction followed by precipitation.
IX	Ion Exchange process where resin or activated carbon selectively adsorbs ionic species from the PLS. Once loaded the resin or carbon is eluted via specific process to produce a strip solution in which the sought metal(s) are considerably upgraded and purified. The strip solution then passes to electrowinning or other processing to produce the final product(s).
Extractant	Chemical used to selectively extract a metal ion at one ionic condition (pH or a salt concentration) and stripped of that metal at another condition. Extractant mixed with Diluent to produce the Organic.
Resin	A porous plastic bead containing a specific chemical(s) which can selectively extract the sought metal ions under certain conditions and release then (elute) them under other conditions.
Diluent	A refined paraffin or solvent with a high flash point to reduce SX fires.
Organic	A mixture of Extractant and Diluent
Bleed	The excess solution that is removed from the circuit for either water balance issues or for the recovery of a primary or secondary element.
Lift / Lift Height	The ore evenly placed / stacked on each lift on the leach pad at a certain lift height. Lift upon lift are stacked with a bench set back on each lift for stability.
GAC (acid systems)	Gangue Acid Consumption – the acid consumed by gangue minerals not resulting in the dissolution of payable metals
GLC	Gangue Lixivant Consumption – the lixiviant consumed by gangue minerals not resulting in the dissolution of payable metals
Percolation	The movement of leach solution (BLS / ILS) through the Dump, Heap or Vat measured in $L m^{-2} h^{-1}$
Drip Irrigation	The application of the BLS / ILS via poly tape pipes spaced closely on the pad. Results in less evaporation
Wobbler	Type of specialised sprinkler for application of BLS / ILS to heap leach.
Agglomeration	(or Pelletisation) The binding of fines within an ore or concentrate to form larger particles by using a binding agent and mechanical means. Undertaken to ensure better percolation and thus better recovery.
Ponding	Pooling of solution and lixiviant on top of a heap leach due to poor percolation. Detrimental to heap performance and recovery.

1.4. Percolation Leach pH Range

Commercial Percolation Leaching can be performed over the entire pH range:

Acidic	Sulphuric, Hydrochloric, Organic Acids +/- microbes <ul style="list-style-type: none">• Recovery of base metals, uranium & liberation of precious metals from refractory sulphides.
Neutral	Salt water, raw water +/- fungi & microbes <ul style="list-style-type: none">• Recovery of alkali, earth and base metal salts, novel processes for base and precious metals.
Alkaline	Cyanide, bicarbonates, thiourea, ammonium salts <ul style="list-style-type: none">• Recovery of gold, silver, uranium

1.5. Range of Commercial Percolation Leaching

Commercial percolation leaching covers a wide range of minerals and applications and lixivants. Novel applications of percolation leaching number considerably more with a broader range in lixivants and minerals possibly processed. These novel percolation leach processes are generally prevented from taking the step to commercialisation due to either;

1. The lixivant consumption and or GLC rates and thus the unit cost per tonne of ore;
2. The lixivant stability, toxicity or availability in commercial quantities;
3. The lixivant cost versus metal recovery (revenue);
4. The ability to selectively extract the metal(s) from solution;
 - a. The ability to extract the metal(s) from solution without neutralising the lixivant;
 - b. Thus the ability to recycle the lixivant in the BLS.

The ability of a process to meet the above criteria is rare and this is explained in further detail below.

1.6. Percolation Leach Categories

Commercial Percolation leaching is generally grouped into the following:

- | | | |
|----------------------------------|--------|-----------------------------------|
| 1. In-situ Leach | (ISL) | (Under Ground) |
| 2. Dump Leach | (DPL) | (Run Of Mine ore) |
| 3. Heap Leach | (HPL) | (Crushed and or Agglomerated ore) |
| 4. Vat Leach | (VTL) | (Ore or Concentrates) |
| 5. Agglomerated Fines Heap Leach | (AFHL) | (Ore or Concentrates) |

The types of percolation leaching commercialised are tabulated below with a summary of the applications.

Table 1. Summary of Types of Percolation Leaching and Typical Criteria.

Type	Particle Size (p80 mm)	Crushed	Agglom- eration	Irrigation Rates (Lm⁻² h⁻¹)	Lift Height (m)	Leach Time (Years)	Recovery (typical)	Relative CAPEX (LOM)	Relative OPEX (LOM)
ISL	>1000 mm	Can be In-situ Blasted	NA	Wide and varied	na	Cu: >5 U: 1-3	5-50%	50%	50%
DPL	1000-30 mm	No	No	2-15	8-75 m	Cu: >10 Au: 2-6	20-85%	40%	30%
HPL	100-5 mm	Yes	Mostly	2-15	2-10 m	Cu: 1-4 Ni: 1-5 U: 1-3 Au: 0.1-2	40-97%	100%	100%
VTL	10-0.5 mm	Yes	Maybe	10-50	1-5 m	4-30 days	80-97%	130%	150%
AFHL	1-0.25 mm	Yes & or milled	Yes	2-15	1-5 m	As per heap leach	70-97%	130%	150%

Table 2. Summary of Commercial Applications of Percolation Leaching.

Type	Acidic Leach	Alkaline Leach
ISL	<ul style="list-style-type: none"> ○ Base metals from sandstones or old stopes. May include Biological leaching. All with sulphuric acid lixiviant <ul style="list-style-type: none"> ○ U, Cu, Ni 	<ul style="list-style-type: none"> ○ Uranium from sandstones with sodium bicarbonate lixiviant solutions.
DPL & HPL	<ul style="list-style-type: none"> ○ Base metal oxide ores with sulphuric acid lixiviant; <ul style="list-style-type: none"> ○ Cu, Ni, U, Co, Zn etc ○ Bio-Leaching of transitional and sulphide base metal ores and gold ores with sulphuric acid lixiviant; <ul style="list-style-type: none"> ○ Cu, Ni, Au (Au ores, washed, neutralised & heap leached with cyanide lixiviant) ○ Oxidised gold ores with thiosulphate lixiviant; 	<ul style="list-style-type: none"> ○ Uranium ores with sodium bicarbonate lixiviant solutions. ○ Oxidised ores with cyanide; <ul style="list-style-type: none"> ○ Au, Ag ○ Oxidised ores with ammonium thiosulphate; <ul style="list-style-type: none"> ○ Au, Cu (poor Ag recovery) ○ Oxide ores with ammonium sulphate; <ul style="list-style-type: none"> ○ Cu
VTL	<ul style="list-style-type: none"> ○ Base metal oxide ores with sulphuric acid lixiviant; <ul style="list-style-type: none"> ○ Cu, Ni, U, Co, Zn etc 	<ul style="list-style-type: none"> ○ Oxidised ores with cyanide; <ul style="list-style-type: none"> ○ Au, Ag
AFHL	<ul style="list-style-type: none"> ○ Base metal oxide ores with sulphuric acid lixiviant; <ul style="list-style-type: none"> ○ Cu, Ni, U, Co, Zn etc ○ Bio-Leaching of transitional and sulphide base metal ores and gold ores with sulphuric acid lixiviant; <ul style="list-style-type: none"> ○ Cu, Au (Au ores, washed, neutralised & Heap leach with cyanide lixiviant) ○ Oxidised gold ores with thiosulphate lixiviant; 	<ul style="list-style-type: none"> ○ Oxidised ores with cyanide; <ul style="list-style-type: none"> ○ Au, Ag ○ Oxidised ores with ammonium thiosulphate lixiviant; <ul style="list-style-type: none"> ○ Au, Cu (poor Ag recovery) ○ Oxidised ores with ammonium sulphate lixiviant; <ul style="list-style-type: none"> ○ Cu

Table 3. Specific Examples and Scale of Commercial Percolation Leaching.

Type	Acidic Leach	Alkaline Leach
ISL	<ul style="list-style-type: none"> ○ Uranium ISL, sulphuric acid <ul style="list-style-type: none"> ○ Beverley Mine, Australia (sandstone) ○ Copper ISL, sulphuric acid <ul style="list-style-type: none"> ○ Mufulira, Zambia (sandstone) 	<p>ISL accounts for 41% of world uranium production – mostly with sodium bicarbonate lixiviant leaching of sandstones</p> <ul style="list-style-type: none"> ○ Uranium ISL, sodium bicarbonate
DPL & HPL	<p>DL + HL produces around 20% of the worlds copper;</p> <ul style="list-style-type: none"> ○ Copper DL, sulphuric acid; <ul style="list-style-type: none"> ○ Low grade dumps in N & S America leaching for > 20 yrs with SXEW ○ USA, South America, Australia etc. ○ Sub Arctic to Desert climates ○ Copper HL, sulphuric acid <ul style="list-style-type: none"> ○ HL is by far the most extensive bacterial leach process for recovering copper from secondary copper minerals. ○ Gold liberation via Bio-HL (bio-leaching) of refractory transitional and sulphide gold ores, sulphuric acid; <ul style="list-style-type: none"> ○ Mt Leyshon, Australia ○ Nickel HL, sulphuric acid, Laterites and sulphides <ul style="list-style-type: none"> ○ Greece, European Nickel, Finland etc ○ Uranium HL, sulphuric acid + ferric <ul style="list-style-type: none"> ○ Lagoa Real, Caetité, Bahia, Brazil, China, Argentina ○ Gold Heap Leach with thiosulphate, Newmont, USA 	<p>DL + HL produces around 12% of world gold</p> <ul style="list-style-type: none"> ○ Gold DL Au, Ag with cyanide; <ul style="list-style-type: none"> ○ USA, Australia etc ○ Gold HL Au, Ag with cyanide; <ul style="list-style-type: none"> ○ USA, Australia etc (>120 operations worldwide) ○ Oxidised with ammonium thiosulphate; <ul style="list-style-type: none"> ○ Au, Cu (poor Ag recovery) ○ Oxide ores with ammonium sulphate; <ul style="list-style-type: none"> ○ Cu
VTL	<ul style="list-style-type: none"> ○ Base metal oxide ores with sulphuric acid; <ul style="list-style-type: none"> ○ Cu, Ni, U, Co, Zn etc 	<ul style="list-style-type: none"> ○ Oxidised ores with cyanide; <ul style="list-style-type: none"> ○ Au, Ag
AFHL	<ul style="list-style-type: none"> ○ Biobleach of refractory gold concentrates <ul style="list-style-type: none"> ○ GeoBiotics™, BioHeap™ ○ Bio-Leaching of transitional and sulphide base metal ores and gold ores; <ul style="list-style-type: none"> ○ Cu, Au (Au ores, washed, neutralised & heap leach with cyanide) ○ Oxidised gold ores with thiosulphate; 	<ul style="list-style-type: none"> ○ Silver ore, dry milled, agglomerated, heap leach <ul style="list-style-type: none"> ○ Bolivia

1.7. The Magic Bullet for Copper Heap Leach!

As one can see for the history of heap leaching, agitation leach (using similar lixivants respectively) has predated heap leaching. This is due to one very important aspect of why some types of heap leaching are commercially successful (U, Cu & Au) and some remain novel ideas or under commercialised (Zn, Ni & Co).

The reason is simply the ability to achieve high rates of recovery of the metal from low grade solutions without destroying the lixivant. This enables a more economic process in which the BLS is returned to the heap leach without additional lixivant losses.

Copper solvent extraction has often been described as the magic bullet for heap leaching of copper ores. Since the development of the LIX reagents in the 1960's by Henkel the SX industry has grown considerably. The Magic Bullet was the fact that the copper SX reagents (LIX63 being the first in 1963) could selectively extract copper from low tenor acidic PLS without any neutralisation. This allowed the leaching of low grade ores and the return of the BLS containing the incoming and ion exchanged sulphuric acid. The other 'magic' was that the copper SX reagents were selective over the other ions in the PLS such as iron (ferrous & ferric), manganese, magnesium, zinc, cobalt, calcium etc. Thus SX combined with EW allowed the direct production of high grade 99.99% Cu cathodes (four nines / LME Grade A) from low grade copper ores. The further development of copper extractants over the past four decades has resulted in extractants that can solvent extract copper over a greater pH range, with a higher selectivity for copper over iron and other associated metal ions.

1.8. The Magic Bullet for Gold Heap Leach!

Similarly in the 1970's the IX process for the recovery of gold using activated carbon was becoming commercialised. Carbon In Solution (CIS) IX gold recovery systems allowed the recovery of sub ppm gold values and thus the development of gold heap leaching of lower grade ores. Just as Cu SXEW replaced cementation of copper on iron, activated carbon IX replaced Merrill Crowe precipitation of gold and silver on zinc dust.

Cu SXEW and Activated Carbon IX were the magic bullets for copper & gold heap leaching respectively and those processes are principally responsible for the massive increase in copper and gold production from heap leaching throughout the 1970's, 80's & 90's and remain essentially the same to date.

Agglomeration with cement and or lime was first developed for use in gold and silver heap leaching but the technology saw a transfer to copper heap leaching in the early 1990's with the use of concentrated sulphuric acid as the agglomerant. Subsequently other binders (similar to flocculants) have been used and marketed but sulphuric acid remains the predominate choice in copper agglomeration.

1.9. The Musket Slug for Uranium

The use of IX and SX for the recovery of uranium pre dates both copper and gold and was a result of the nuclear arms race in the 1950's. The first commercial use of amines in uranium extraction from

leach solutions was at West Rand Consolidated Mines in South Africa in 1952. The reason it is described here as a Musket Slug rather than a Magic Bullet is that the extraction was not overly selective and required subsequent purification. The development to produce a more selective extraction process for uranium took several decades. The uranium SX and IX processes gradually became more selective and more efficient and by the 1980's SX was the predominate process. IX made a comeback for ISL operations where very dilute PLS predominated.

The recovery of uranium from a heap leach or ISL can be achieved with several different lixvants including sulphuric acid and sodium bicarbonate in an alkali solution.

1.10. No Magic Bullet for other Base Metals

The heap leaching of nickel, cobalt, zinc and many other base metals is quite feasible and recoveries of over 85% have been achieved in pilot testwork on laterites, other oxides and sulphides of these and many other base metals. The reason the heap leaching of nickel, cobalt, zinc and others hasn't yet been commercially successful is not because of any heap leaching issues but simply because the SX reagents or IX exchange resins do not exist to recover these metals without significant pH modification to the PLS and or neutralisation of the sulphuric acid lixivant.

If there existed a SX reagent that could selectively extract dilute nickel from a PLS solution at pH 1.5 and produce a >50 gpl strip solution, then a majority of the worlds nickel would today, be produced via heap leaching. The same applies for zinc, cobalt, manganese and several other elements that could be potentially produced by heap leaching except that they lack a magic bullet extraction process!

2. Heap Leaching

The largest producer of mining revenues within the percolation leach industry options is Dump / Heap Leach and the remaining of this paper focuses on the Art of Heap Leach. The general use of 'heap leach' below shall, unless specific, refer to both heap and dump leaching.

2.1. Why Heap Leach ?

Heap leaching is generally the chosen process for a low grade ore body that doesn't warrant the OPEX or CAPEX of milling and intensive processing but also may be chosen to minimise risk or maximise financial return compared to a more capital intensive agitated leach process.

A heap leach project can often be the first stage in the longer term development of a project and can allow a small company to establish an operation which can pay for further resource development and funding of the second stage development. A heap leach operation often focuses on the open cast mining of the oxide resources and a second phase would tackle the underlying sulphides with underground mining and a suitable process for the sulphide ore. The second phase is often a hybrid process which takes advantage of the respective positives of the various processing options and the range of ore types.

Heap or dump leaching can also be considered as a means to pay for the stripping of a higher grade ore body. In this case the heap leach need only pay for itself and the associated mining thus effectively reducing the strip ratio (cost of mining) for the primary milling operation.

Heap leaching may simply be a better option than milling and agitated leaching for a combination of metallurgical and financial reasons. Comparative studies on the financial returns between heap leaching and milling / agitation leaching are not new. At the joint AIME/AusIMM Symposium "World Gold '91", P. Philip presented a paper "To Mill or to Leach?" in which he evaluated the decision of Newmont to build the No. 3 mill at Carlin. His conclusion was that the mill recovery was over-estimated and the heap leach recovery underestimated, and thus the decision to go with milling may have been incorrect.

A review (Kappes, 1998) concluded that for a "typical" Nevada type oxidised gold ore body with an ore grade of 3.0 grams gold per tonne, the mill recovery would have to be at least 21 percentage points higher than the HPL recovery to achieve the same return on investment - and this is very seldom the case.

A silver heap leach operation at Potosi, Bolivia, showed the same recovery in both heap and agitated leach testwork. The silver ore however leached very slowly and residence time of up to 4 days was needed in an agitated leach plant which would require considerable CAPEX. Although the heap leach took several months to achieve the same recovery, the economics clearly favoured the heap leach option.

The financial returns of a heap leach project often seem to be excellent based on laboratory testwork and scale up assumptions. The notion of heap leaching seems simple and this can often mislead the inexperienced. In fact heap leaching is a complex engineering and metallurgical process requiring meticulous design, engineering and experience in the Art of Heap Leach, if it is to be a success.

2.2. Basic Design Considerations

A heap leach design must take into account many variables and is a truly multidiscipline process with all parties needing to pull together to get it right. The following aspects covered by various disciplines are essential to ensuring a commercially successful heap leach project.

1. Geology
 - a. Resource definition ensuring the Reserve identified is leachable;
 - b. REPRESENTATIVE samples for leach testwork;
2. Mining
 - a. Blasting to produce appropriate size reduction and micro fracture;
 - b. Blending of ore critical for not only grade but mineralogy and GLC normalisation;
3. Metallurgy
 - a. APPROPRIATE leach testwork. Large diameter column leach or pilot heaps;
 - b. Agglomeration testwork;
 - c. GLC / GAC versus pH, flux and time;

- d. Scale up factors;
- e. Extraction process, water balance;

- 4. Engineering
 - a. Pad and pond designs for 1 in 100 / 500 year rainfall events;
 - b. Process design, bleed systems, extractive metallurgy;
 - c. Agglomeration & Stacking systems;
 - d. Synergy of hybrid operations;
 - e. Operating procedures;

- 5. Geotechnical
 - a. Ground stability;
 - b. Heap stability;

- 6. Human Resources
 - a. Mechanised or labour intensive;

- 7. Environmental
 - a. Water balance and sampling;
 - b. Stockpiling top soils;
 - c. Revegetation plan at end of mine life;

Various aspects of the above are well covered by several texts and by many papers that have been published over the past 30 years on each of these design and operation aspects. General References at the end of this paper are suggested reading on such. It is not the intention nor the capacity of this paper to cover such design detail. Aspects of design that are discussed herein are those that which may not be well covered in texts and are specific to developing the explanation of the Art of Heap Leach.

2.2.1. Basic Design Criteria Comparison for Precious and Base Metal Heap Leaching

The difference between the heap leaching of precious metal ores or base metal ores is simply one of metallurgy and materials of construction. Both benefit from proper construction to ensure good percolation and aeration of the ore.

Table 4 Design Criteria Comparison for Precious and Base Metal Heap Leaching

Typical Criteria	Copper / base metals	Gold / Silver
Ore Type	Oxide & or Transition	Oxide & or Transition or flake native
Leach time Heap Leach	90 to 500 days	15 to 45 days
Leach time Dump Leach	300 to 3000 days	30 to 300 days
Lixivant	Sulphuric acid Sulphurous acid Acidified brine Acid and ferric ions	Cyanide Thiourea Thiosulphate
BLS pH	0.3 to 3	9 to 13
BLS [Lixivant]	5 to 15 gpl acid	200 to 400 ppm NaCN
Other reagents	Fe ₂ SO ₄ , SO ₂	NaOH, Anti-scalant
Agglomerant	98% H ₂ SO ₄	Portland cement / lime
Bioleaching	Often – even when not intended	Some novel processes
GAC / Gangue Lixivant Consumption	-20 [#] to +100 kg t ⁻¹ acid	0.2 to 1.5 kg t ⁻¹ NaCN
Typical Metal Recovery	SXEW / Direct EW	CIS / IX / EW
Typical Materials of Construction	VLDPE / HDPE FRP / 316L / 904L SS (No copper, brass or galvanising)	VLDPE / HDPE Carbon steel (No copper, brass or galvanising)
Typical PLS Tenor	3 to 15 gpl Cu	0.5 to 5 ppm Au
Typical BLS / RAF Tenor	50 to 100 ppm Cu	0.01 to 0.05 ppm Au

2.2.2. Heap Construction

Agglomerated ore requires curing and then respect in handling and stacking on the heap to avoid breaking up agglomerates. Retreating stackers and grasshopper conveyors can in themselves be a significant CAPEX. Although all heap leach ore deserves a lot of respect in handling, de-slimed ore can be more readily handled.

Depending on the crush size, the ore may even be amenable to back dumping from the top face of an advancing lift – something which MUST NOT be done with any conventional heap leach as this has resulted in many heap leach failures due to compaction. Heap construction must involve a major focus on eliminating all forms of compaction. Irrigation, pedestrian traffic and certainly mobile equipment all cause compaction and must be minimised or eliminated from the top of a fresh heap leach lift.

2.2.3. Gangue Acid (Lixivant) Consumption (GAC / GLC)

The viability of a heap leach operation often depends heavily on the rate of GLC and the cost of the lixivant. As the price of sulphuric acid rises some copper heap leach operations become unviable and vice versa. Where acid is free FOB GAC is of little concern. However greenfield mines which need to import acid suffer a sensitivity to acid price relative to the GAC of the ores they process.

The heap leaching of nickel laterites is problematic in that the GAC is around 500 kg/t and this has also restricted the commercialisation of nickel heap leaching. Typical GAC for a copper heap leach is 10 to 40 kg/t H₂SO₄ acid and GLC for a gold heap leach is 0.3 to 1 kg/t NaCN. Ultimate GAC of a base metal ore often increases with leach time and with poor percolation. It is thus imperative to achieve maximum permeability to avoid severe pH differentials through the lift.

2.2.4. Permeability

The most fundamentally important aspect of heap leaching is permeability of the leach and even percolation of the lixivant solution throughout all the ore. The failure to achieve a permeable heap will reduce recovery due to several reasons including:

1. Incomplete lixivant access to ore. Not all of the ore is leached simply due to the inability of the lixivant to permeate to the minerals and for the dissolved metals to be rinsed out. Shrinking core model on a macro scale;
2. Decreased percolation rates depriving first order reactions of lixivant, dissolved oxygen and the dilute solution to rinse away dissolved metals;
3. Increased residence time (longer reaction time and thus complete consumption of the lixivant) of leach solution in the heap resulting in wide pH profiles and precipitation of metals (Fe, Co, Au) often exacerbating the percolation problems;
4. Decreased oxygen levels in heap from natural or forced ventilation;

2.2.5. Agglomeration

Oxidised ores typically contain significant quantities of fine minerals such as clays, phyllite or laterite type oxides. Considering the basis of heap leaching is the construction of a heap through which a leach solution is passed – the presence of such fines is significant factor in achieving the required percolation rate.

Agglomeration can to a certain extent overcome this problem and if proper agglomeration is achieved in actual operations (as opposed to laboratory testwork), agglomeration can cope with an almost entirely clay ore or a mineral concentrate with a p80 of 100 micron, albeit at a cost.

2.2.6. De-sliming versus Agglomeration

High percolation rates are essential in ores which have a high GLC and de-sliming may be an option in such cases. If percolation is medium to low, precipitation of ‘just leached’ metals may occur in the

resulting active band. De-sliming may be undertaken for other reasons including the recovery of native metals from the fines or to treat the higher grade fines separately in a mill / agitation leach.

3. The Art of Heap Leaching

3.1. Heap Leach Failures

Whilst heap leach projects can be quite financially successful they more often than not produce less than feasibility projections. In 1979 Dan Kappes presented a paper "Heap Leaching - Simple Why Not Successful?" – which reviewed existing gold & silver heap leach projects. Kappes concluded that 50% of them were failures. In the 32 years since then many more heap leach operations have failed – including a considerable number of undercapitalised and small operations. From the authors experience throughout the 1990's to date at least 25% of heap leach operations around the world fail to produce a return on CAPEX.

The reasons for the failure of the heap leach operations around the world include; a lack of representative testwork samples, failure to fully evaluate or scale up metallurgical testwork for full scale heap leaching and or a lacking in the methodology / design of the heap leach operation.



Figure 4 Sanyati copper heap leach failed due to poor percolation (1999)

3.2. Background

The reasons for poor heap leach performance are normally compaction from careless heap stacking and the presence of fines which tend to migrate within the heap and eventually block or channel the percolation of leach solution. Agglomeration helps to bind these fines into larger agglomerates thus limiting migration and keeping the heap permeable.

Compaction and fines migration result in poor percolation of leach solution which then affects the chemistry of leaching resulting in poor recovery and often higher reagent consumption's. Due to channelling or simply that the leach solution cannot penetrate into the ore, only a fraction of the stacked tonnage is actually leached which is the primary cause of lower metal recovery.

3.3. Macro particles and Models

Understanding macro particles in heap leaching is fundamental in understanding and analysing recovery. Micro particles have been well discussed in literature and form the basis of many leaching models. These all revolve around the concept of a shrinking core in which a lixivant diffuses into a micro particle (crushed ore of say 25mm), dissolves the metal and the metal then diffuses back out to the surface of the micro particle from where it is then washed / rinsed away into the PLS by the bulk of the BLS.

As such the leaching is constrained by lixivant supply to the surface of the particle and the leaching is diffusion controlled. However the overall reaction in a heap leach depends on the mineral and lixivant. Leaching of high grade copper oxide ore is a first order lixivant controlled in so much as the lixivant supply to the mineral surface is constrained by lixivant concentration and percolation rate. However in low grade copper and oxide gold heap leaching the reaction is more diffusion controlled as the lixivant is mostly present in excess. Figure 5 shows a simplified shrinking core.

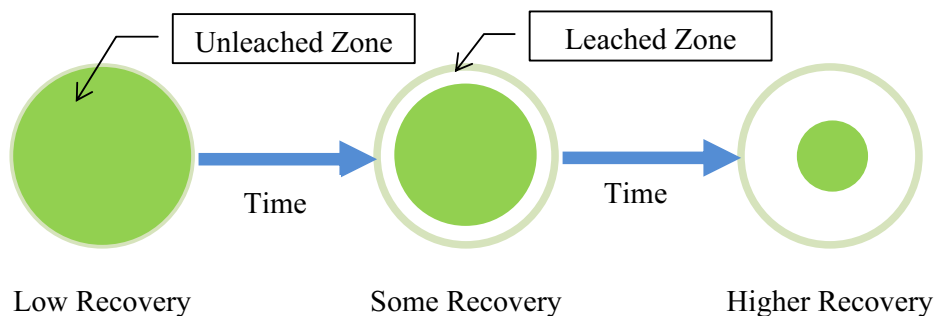


Figure 5 Shrinking Core Leaching Simplified

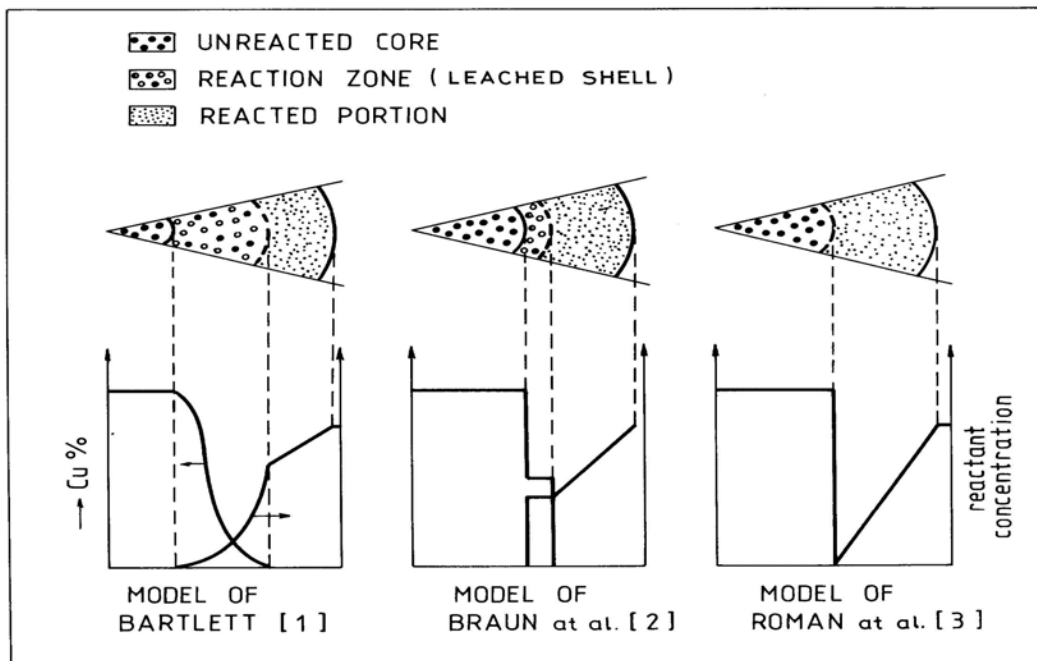


Figure 6 Shrinking Core Model Comparison

Figure 6 shows three very good representations of the interactions of lixivant (reactant) diffusing in, reaction with the unreacted (unleached) minerals and metal salts diffusing out of a shrinking core leaching particle (rock). Such models and variations are correct in so much as they predict recovery from individual particles in an ideal heap in which percolation is perfectly uniform and thus lixivant well distributed. In reality this is never the case as even in a de-slimed heap leach some channeling occurs and perfect distribution is practically impossible.

These different models do however show how the lixivant concentrations and metal tenors can vary in a leaching particle. It is the opinion of this author that all three models are within reason a fair representation of shrinking core leaching in one heap leach operation due to the variety of rock / micro and macro particle composition and porosity.

In a heap leach in which equipment travels on top of a new lift or where agglomeration is poor, compaction results in macro particles. These large particles as depicted in Figure 5 can be of any shape and can be many metres across. These particles leach as predicted by the various shrinking core models which also reasonably predict the leach time required. For a 25mm particle the leach time may be 90 days but for a macro particle of several meters across caused by equipment compaction of agglomerates, the leach time is several years.

Understanding the effect of macro particles and the prevention of such by careful design and management of heap leach stacking is fundamental to the art of heap leaching.

3.4. The ‘Channel Effect’ in Heap Leaching

Now consider the PLS solution coming from the bottom of a heap. Regardless of how well or poorly a heap is percolating, the PLS solution is actually a combination of individual fractions of the irrigated BLS that have passed through the heap, some with less residence time than others. Some of which have taken magnitudes more time to pass from top to bottom than other fractions. Some solution has spent months diffusing into a particle with lixivant and diffusing out with dissolved metals. Some solution has simply passed through only performing a rinsing function.

When recombined at the bottom of the heap the PLS is an average of all the individual fractions – all with a wide range of time spent percolating to that point. Some fractions would have channelled through the heap and will be high in lixivant concentration and relatively low in metal values. Some PLS fractions would have passed in average or expected time and will be almost depleted in lixivant and have relatively high metal values. Some BLS fractions would have passed through the heap very slowly time and will be depleted in lixivant and possibly depleted metal values due to precipitation within the heap.

However as these solutions recombine to form the PLS at the drain of the leach pad the chemistry of the solutions are immediately weight averaged on mixing. This is referred to herein as the Channel Effect and is the reason many heaps are incorrectly written off as having unsuitable mineralogy / ore type.

In most cases however it is not the mineralogy or metallurgy of the ore but rather the physical nature of the heap which is a product of crushing, de-sliming / agglomeration, stacking and irrigation.

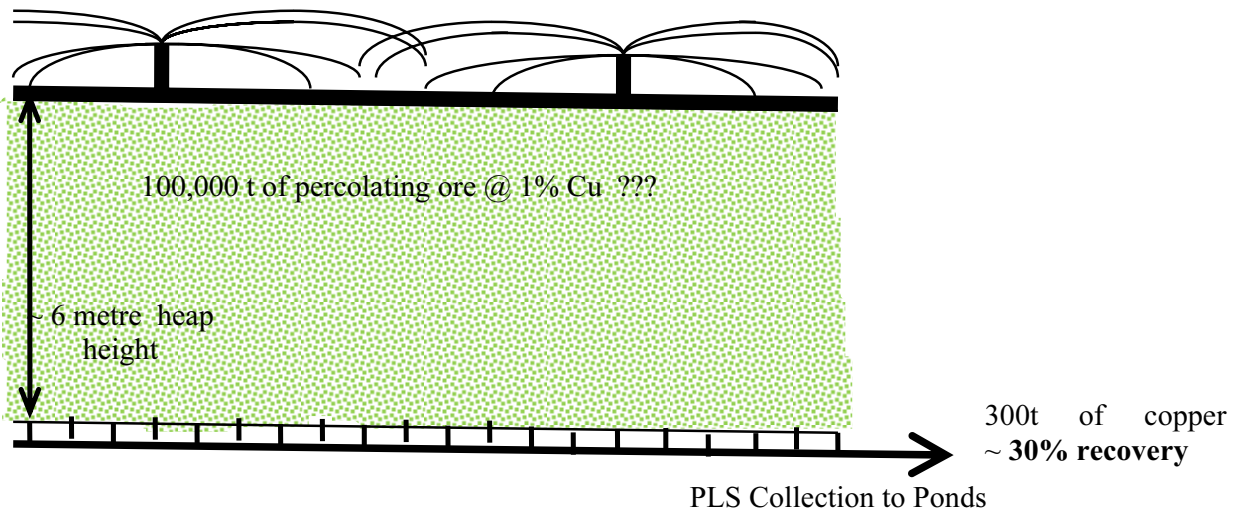


Figure 7 Hypothetical Heap Leach with Poor Recovery

Table 5 Actual and Expected figures for hypothetical BLS and PLS samples

	BLS actual	BLS expected	PLS actual	PLS expected
pH	1.3	1.3	2	2
Cu tenor (gpl)	0.1	0.1	1.5	3.5
Ferric tenor (gpl)	0.2	8	0.2	8

Figure 5 **Error! Reference source not found.** depicts a heap leach in which the recovery is poor with the hypothetical assays figures in Table 5. There are a number of possibilities responsible for this poor recovery including poor scale up of testwork, influence of temperature, mineralogy etc. However looking at the fundamentals – i.e. the chemistry of BLS irrigated and resulting PLS it would not seem that there is a problem with BLS solution lixiviant concentration, GAC of the ore or pH control.

- The pH of the PLS is not high enough to precipitate ferric compounds (at pH ~3 ferric precipitates almost irreversibly).
- There is residual free acid – indicating that the ore is being exposed to sufficient lixiviant.
- Thus GAC consumption thus does not seem to be the problem.

From these figures an inexperienced metallurgist may conclude:

- Acid consumption is as predicted as the pH difference seems normal (as per column leach)
- Low copper recovery is blamed upon poor liberation or slow leaching minerals

- Lack of ferric generation is blamed upon poor biological activity.

Usually as a result the mineralogy gets blamed and condemned as not suitable to heap leach. Sometimes the course of action taken is to prescribe finer crushing or an increase in the lixivant concentration. Those conclusions would in fact worsen the situation and overlook the real problem of channelling and poor percolation. Based on the overall recovery and these figures it would be easy to write off this ore / heap leach thinking that the mineralogy is the problem.

In fact the ore that has leached has leached quite well – but only in sections that have reasonable percolation. The regions of the heap that have been compacted are leaching as macro particles and other regions with much lower percolation are retaining leach solution for long periods, depleting the acid and thus allowing the precipitation of ferric salts such as jarosite.

What the metallurgist is seeing in the PLS assay's is a combination of a number of solutions that have a wide range of residence times. Due to the logarithmic nature of pH, a solution with a high pH can be mixed with a small amount of solution of low pH and the pH will still be low. 10% of BLS at pH 1.3 mixed with 90% PLS at pH 4 gives a solution of around pH 2.

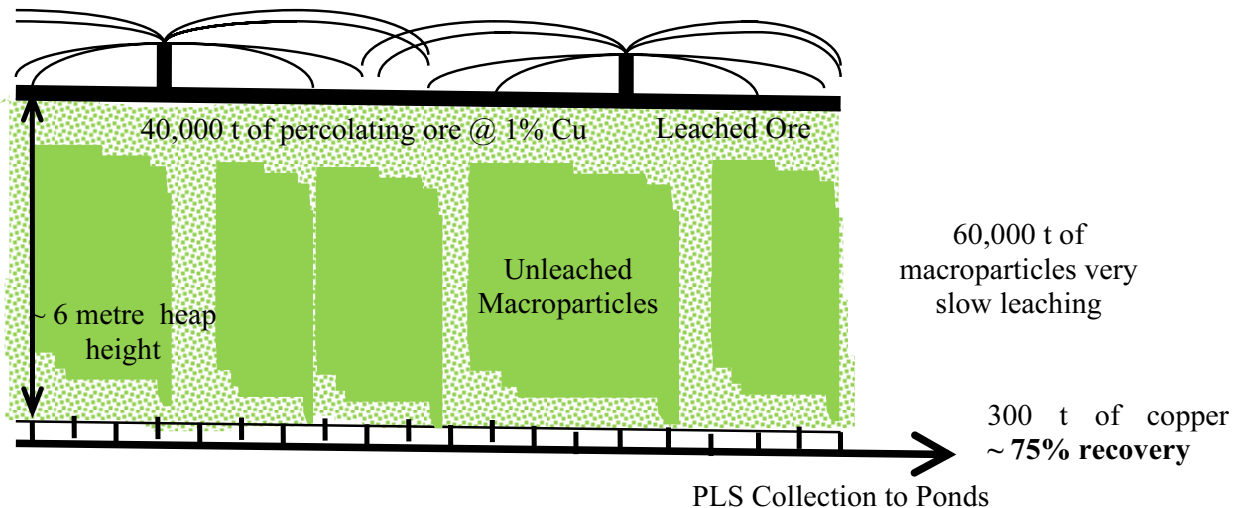


Figure 8 Hypothetical Heap Leach with Percolating ore and Non Percolating Macroparticles

Figure shows the macroparticles in the hypothetical heap leach. The 300t of copper recovered is not from 100,000t of ore but rather 40,000t of ore that was actually available for leaching. The remainder of the ore is locked up in macro particles that will take years to leach. The ore did in fact leach well and there are not mineralogical or metallurgical problems. If the ore was agglomerated, de-slimed and or stacked correctly the overall tonnage leached would be close to 100,000t and the recovery could be expected to be significantly improved.

3.5. Pre-lixivation

How, when and at what rate the lixivant comes into contact with the ore is naturally also very important. Prior to the concept of pre-lixivation in the early days of heap leaching it was common to stack the ore on a pad and then irrigate with BLS containing a high dose of lixivant whose concentration was only governed by the cost. A higher acid concentration for example, was needed to overcome the initial acid consumption in the upper region of the heap and yet still deliver acid to the lower heap. Over time the acid depleting capacity of the upper heap would drop off allowing more and more acid to percolate without neutralisation, to the lower regions. This was naturally very inefficient and resulted in very slow recoveries.

Several factors which reduce recovery in a heap that is stacked without any lixivant added include:

- The lixivant being consumed by upper layers of ore in the heap depriving the lower regions;
- Channelling where by dry spots occur within the heap and are never leached;
- Incomplete coverage of irrigation due to spacing and winds thus leaving sections of ore without any lixivant.

In these cases, ore is simply not leached due to insufficient lixivant. In both precious and base metal heap leaching it was found that pre-lixivation resulted in far superior leach recovery in terms of both extent of recovery and rate of recovery.

Figure shows the leaching band working its way down through a heap leach lift limited by the amount of lixivant that can be reasonably and economically added to the top of the heap.

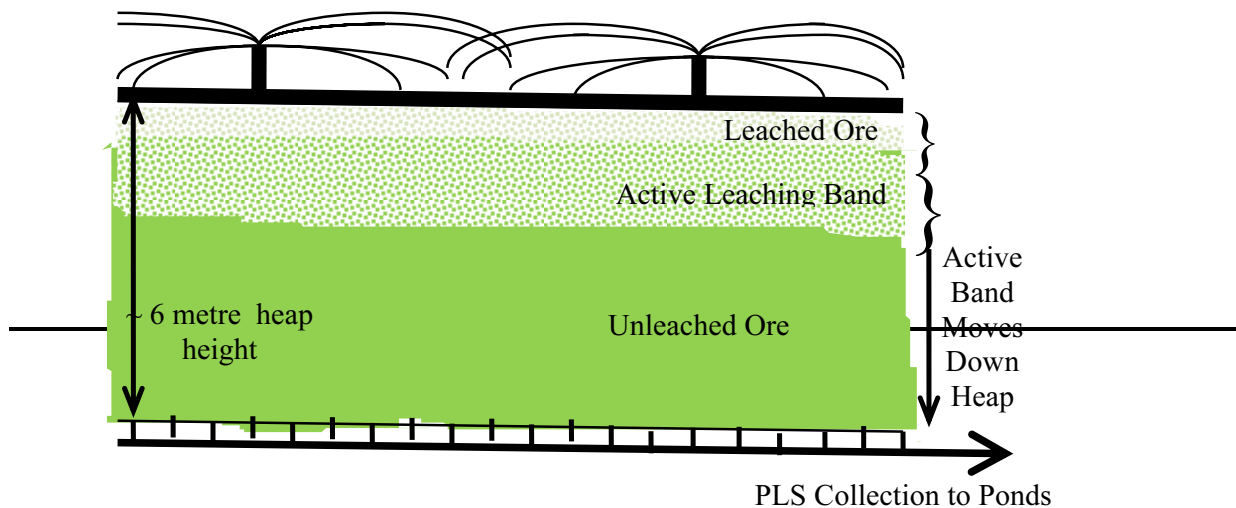


Figure 9 Active Leaching Band Progressing Slowly Down a Heap Leach Lift

Pre-lixivation or pre-acidification can overcome most of these disadvantages. Agglomeration of copper oxide ore with concentrated H₂SO₄ has become an industry standard due to the dual benefits of improved percolation and pre-lixivation of acid onto the ore. No doubt it will also become the industry standard with nickel laterite and zinc oxide heap leaching as well as such become commercialised.

The benefits of pre-lixivation are considerable and include:

- All ore is dosed with the correct rate of lixivant rather than hoping irrigation and percolation will distribute lixivant solution to 100% of the ore (which is very unlikely);
- Better pH control through absolute distribution of the acid / alkali onto the ore;
- Wetting of dry un-agglomerated ores prior to stacking results in higher percolation due to pre expansion of clays;
- High PLS tenors are achieved in the first rinse (~30gpl Cu from a 2% Cu ore and 10ppm Au from a 1gpt Au ore).

In copper ore the addition of concentrated acid in the agglomeration step results in a very aggressive high temperature attack of copper minerals which is not possible once in the heap. Similarly gold ores are dosed with ~1000 to 2000ppm cyanide solution which speeds up the diffusion controlled reactions by increasing the rate of lixivant diffusion due to distribution and concentration gradients. Both result in higher initial and overall recoveries.

With pre-lixivation with acid for copper and cyanide for gold ores, the oxide ore is effectively leached by the time it is stacked and the heap leach process is initially just a rinsing process. Pre-lixivation also overcomes a significant negative of dosing lixivant into the BLS which results in additional lixivant losses to the wind and to UV degradation (cyanide has a half life of ~6hrs in sunlight).

Dump leach operations and several heap leach operations still operate without pre-lixivation due to practical issues of adding solution to the back of dump trucks and tramming over sodden ore. However efforts are and should be made to overcome these issues for the obvious benefits.

3.6. Heap Leach Design Criteria

The big question always asked is how to scale up laboratory metallurgical results to a commercial design. Several models exist and the most successful are empirical models based on very similar ore

and criteria. However the fundamental rule of models applies to percolation leaching just as much as anywhere else; rubbish in equals rubbish out. Poor data cannot give you good estimates.

Even the best heap leach models have failed to successfully estimate the rate of and ultimate recovery of a heap leach due to reasons including:

- Lack of representivity in the testwork ore samples with respect to minerals, GLC and grade;
- Ore resource or mine plan changed or expanded post metallurgical testing;
- Satellite ore bodies introduced to the mine plan;
- Poor mine grade control or blending of ores to produce a consistent feed to the heap leach operation. Variation in GLC / GAC can have a major effect on recovery times;
- Changing ore types during life of mine;
- Poor management of agglomeration and or heap stacking operations resulting in poor percolation.

It is the option of the author that while models can be used a guide line the major emphasis should be on ensuring the heap leach is agglomerated and stacked with utmost care and with a pragmatic understanding of the art of heap leaching.

3.6.1. Rule of Thumb Scale up

Results from large diameter laboratory column leach testwork conducted in columns of the same height of the proposed heap should be scaled up as follows for use in the financial model as well as design criteria;

Laboratory Results	Rule of Thumb Design Criteria
Column Leach Results Leach period 'T' for certain recovery 'R'	Leach period 300% of T to achieve 80% of R recovery.
Gangue lixivant consumption 'GLC'	150% of GLC / GAC over leach period of 300% of T
Pre-lixivation / agglomeration addition of 'L' kg per tonne	Nominal L kg/t Design 120% L kg /t for all reagents
Average Percolation 'P' achieved in testwork	If P is < 10 L m ⁻² h ⁻¹ then start again with agglomeration or de-sliming if P > 10 L m ⁻² h ⁻¹ Then Nominal irrigation rate of 10 L m ⁻² h ⁻¹ And Design irrigation rate of 15 L m ⁻² h ⁻¹
PLS grade	Calculate assuming leach period 3.T, 0.8.R, lift height, nominal irrigation rate & ore grade after mining dilution. Do not use test work figures for PLS grades.
Ore grade.....	Assume 80% grade of predicted reserves....

Example:

A representative sample of oxide gold ore at 1.5 gpt, was agglomerated with 6 kg/t of cement and pre-lixivated with cyanide solution 0.5 kg/t and leached in a 600mm diameter column with 5m of effective ore. Percolation rates of $> 15 \text{ L m}^{-2} \text{ h}^{-1}$ resulted in no flooding. The gold recovery was 85% after 15 days.

Laboratory Results	Rule of Thumb Design Criteria
85% after 15 days	68% recovery in 45 days
0.5 kg/t NaCN	0.75 kg /t NaCN over 45 days
6 kg/t cement	7.2 kg/t cement for agglomeration
$> 15 \text{ L m}^{-2} \text{ h}^{-1}$	Then Nominal irrigation rate of $10 \text{ L m}^{-2} \text{ h}^{-1}$ And Design irrigation rate of $15 \text{ L m}^{-2} \text{ h}^{-1}$
PLS grade	Mining Dilution 5%, Ore grade 1.2 gpt = 1.14gpt $(1.14\text{gpt} \times 5\text{m} \times \text{SG}1.6 \times 68\%) / (0.01 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1} \times 24 \times 45)$ = 0.6 ppm average PLS tenor.

These are conservative but realistic estimates considering the number of variables that can influence poor recovery. If the financials and engineering design are based on such criteria then success is highly probable with the added benefit of rates of recoveries and thus PLS tenors greater than design criteria estimates – rather than the very embarrassing alternative.

4. Conclusion

While heap leaching produces a major fraction of the worlds copper, gold and uranium, fundamental problems still plague the technology. Heap leach models have provided some understanding but not solutions to the bigger problems. There exists physical factors of design and methodology which govern heap permeability and play a much larger role in the success of a heap leach operation. Even with the best model estimates a heap leach operation will fail if the fundamentals of percolation are ignored. Percolation management is the priority for all heap leach metallurgists as such plays a major

role in heap chemistry and thus recovery. Understanding how to properly interpret PLS assays will take experience but it is hoped the example provided within will assist.

Maximising percolation, understanding the macro particle effect in heap leaching and the prevention of such is a major step towards mastering the Art of Heap Leaching.

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The Author



Lee John, *Chairman and Principal Engineer*, BioMetallurgical (Engineering) and Globe and Phoenix Gold Mining Company (Mining company)

Managing Director and Principle Engineer of BioMetallurgical since 1999 and involved in the design, construction, commissioning and operation of numerous Copper, Cobalt, Nickel, Gold & Antimony projects throughout Southern Africa. Owner of Zimbabwean mining houses; '*Homestake Mining*' & '*Globe and Phoenix Gold Mining Company*', producer of Gold and Antimony as well as '*Zimbabwe Nickel Company*', producer of Copper and Nickel. In 2008/9 undertook an emergency short contract as General Manager of Ruashi Mining in the DRC to finish construction, commissioning and rectify problems of the 45,000 tpa Cu / Co project. 1990 to 2000 worked in projects and operations over three continents in positions of Lead Engineer up to Mine Manager involved in design, construction, commissioning, operation and management.