HEAP LEACHING

By

DAVID MENNE

ABSTRACT

The preferred alternatives in heap design and their motivation are identified as
- normal heap leaching, to be generally applied wherever possible,
- flooded vat leaching, to be applied where wetted ore lacks adequate cohesion or if limited space necessitates it,
- thin layer leaching, to be applied where deleterious vat chemistry necessitates it.

A number of the following features would probably be incorporated in the optimization of normal local heap leach operations:
- pre-cyanidation
- pre-agglomeration
- retaining walls
- staged (counter-current) heap treatment
- control of calcium levels
- reduced pH and trickler irrigation

The following technologies associated with heap leaching are expected to become preferred methods:
- adsorption using high pKa weak-base resin columns or alternatively; staged heap leaching and direct electrowinning (where scaling is controllable and chloride levels are relatively low).
- direct smelting of bullion in gas-fired kilns (for larger installations), or alternatively; Micron-type production of bullion flake by electrodepositon onto aluminium and subsequent treatment with NaOH (for smaller installations).

To overcome many of the problems resulting from chemistry inherent in West Australian gold ores and groundwaters, there is considerable motivation to move away from alkali cyanidation to acid leach technologies.

INTRODUCTION

The occurrence of a smaller oxide cap, accessible by cheap open cut mining and overlying larger sulphide reserves is a common feature of Australian gold deposits.

Furthermore relatively small tailings dumps resulting from early operations abound in each of the Australian goldfields.

Heap leaching provides a low-cost option for economically winning gold from such oxide caps and tailings heaps where the ore grade and/or tonnage or initial availability of water is inadequate to support slurry processing.

Such an approach is particularly attractive to enterpreneurs who of necessity have to limit their initial development expenditures until cash flow can be generated to better delineate an ore body or provide the more substantial infrastructure and facilities required to mine and beneficiate, by slurry processes, gold from the underlying more competent and oxygen-consuming sulphides.

Even where the size and richness of a deposit exploited by open cut mining necessitates slurry processing, substantial quantities of undergrade material are generally also produced, and heap leaching provides a means for economically exploiting much of this material.

However, many heap leach operations have demonstrated a variety of technical pitfalls, which generally reduce cashflow to unacceptable levels even if reasonable total gold recoveries are indicated. In other cases the short-cuts needed to generate profitable cashflows have left fortunes in gold in the residue. Apart from the record provided by Kappes (1979), the pitfalls are not generally recorded (Geldard, 1983).

This paper aims to address the major process options for alkaline cyanide heap leaching and related technology for bullion recovery, and to develop the rationale for deciding between these alternatives. Particular emphasis is placed on avoiding or coping with common technical problems of interest to all existing and potential local heap leach operators.

However, to further cater for the variety of interests represented in this distinguished gathering I have attempted to allocate a quarter of the contents to material which cognoscenti will consider to be old hat, and another quarter to state-of-the-art developments which will be of limited interest to as yet uncommitted entrepreneurs who wish to be provided with hard, testable information only. I ask the indulgence of the one group for the subject matter included for the other.

The specific aspects of heap leaching technology which are considered in this paper include

- selection of heap design
- feed preparation
- gold precipitation, and
- bullion production.

Mining, comminution and heap/vat construction also constitute important aspects. However these aspects cover a vast subject matter which has already been addressed elsewhere (Chamberlain, 1980; Clem, 1982; Geldard, 1983; Heinen, personal communication; Potter, 1981) and will thus not be discussed in this paper.

SELECTION OF HEAP DESIGN

The basic options include:
- Normal heap design, where a free-standing heap is built to a height typically dictated by the available material handling system.
- Flooded heap (vat) design, where a heap is contained within impermeable bunds or walls allowing fully flooded operation.
- Thin layer design, where only a relatively thin advancing ore face is leached.

Normal heap design is generally applied because of simplicity and low cost. Re-usable pads are indicated where:
- pad sealing is costly
- a wide ore size range or risk of compaction necessitates sophisticated placement techniques, and where
- the advantages of such placement techniques justify the cost of double handling the ore.

Vat leaching is generally necessary to prevent unplanned heap runaway should the ore lack cohesiveness on wetting. (It should be noted that even should testwork indicate that runaway will not occur, it is still desirable to place heaps so that if the experts were wrong, the heap will run to a more innocuous target than the gold recovery facilities).

Consideration of plant layout or climate may also necessitate the application of vat leaching.

Thin layer leaching is indicated if ore constituents rapidly deteriorate the capability of leachate to execute its dissolution function. This conclusion is in contrast to the original patented aim of Johnson (1980) to apply thin layer leaching to contain within practical dimensions the problem of fines migration leading to a reduction in heap permeability.

Selection tests to rationally decide between the above alternative heap leach designs include assessment of
- minimum cohesiveness to determine whether flooded operation is necessary, and

- maximum kinetics of base, oxygen or
  cyanide consumption to determine the
 necessity of operating a thin layer
  leach.

A description of the tests advised for these
assessments is beyond the scope of this
article, but can be executed by the Edward L
Bateman Pty Ltd (ELB) laboratory in
Kalgoorlie.

Further testwork related to minimum
acceptable ore comminution, optimal leachate
flux and consequent fines management also
need to be executed. This data will affect
decisions concerning the preparation of feed
prior to heap building and leaching, and is
discussed in the next section.

Retaining walls e.g. the prefabricated
L-shaped storage wall units shown on figure 1
(Reid, personal communication) allows more
material to be stacked on a given pad, in
addition to removing the risk of toe shear or
pad runaway which may exist for some ores
following sufficient rain. The use of such
walls also provides good sprinkler coverage
while avoiding sidewall erosion.

FIGURE 1

PRE-FABRICATED L-SHAPED STORAGE UNITS
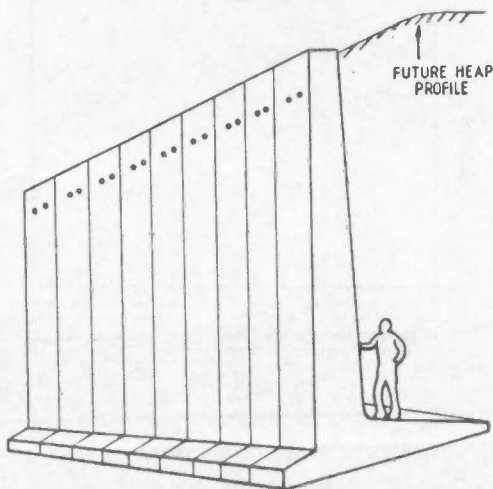
Storage facilities should be provided to
prevent loss of gold if excess leachate flow
occurs following rain or outage of the
irrigation equipment.

In general merely a small surge sump
should separate a normal heap from the
bullion recovery facilities.

To provide for drainage during outage
or rain, a suitably sized pond should be laid
out to take any overflow from this sump.

Evaporation not only leads to excessive
water consumption but also concentrates salts
and increases the occurrence of harmful
precipitates such as those blocking the
nozzles of the irrigation equipment used to
delivery leachate to the heap.

Water management to handle precipitation
problems is very much a 'horses for courses'
issue, which draws on the following
fundamental approaches:

- get and keep calcium levels low
- use equipment resisting and/or
  insensitive to the build-up of
  precipitates [see figures 14a and b
  (Geldard and Houtgraaf, personal
  communications)]
- ensure that precipitates which do
  form are not coherent.

Although the chosen water management
alternatives have facility design
implications, the major issues involve
operations. Thus this subject will be
discussed in the section devoted to heap
operation.

FEED PREPARATION

Comminution is generally a major issue in
feed preparation. Comminution is generally
executed to liberation size, and this may be
best estimated in a firkin roll test:

Typically 100 kg of -32 mm material is
leached in a rolling device (e.g. a 80/120
litre concrete mixer) for an extended period
around 48 hours. The residue after leaching
is screened into a number of size fractions
(typically 32 x 16; 16 x 8; 8 x 4; 4 x 2 and
2 x 1 mm). Each size fraction is then
reduced to a size typically applied to slurry
processing (e.g. 100% under 200 microns) and
further leached for 24 hours.

An analysis of incremental gold
recovery will indicate whether the increased
recovery of gold by slurry processing
excludes heap leaching and if not, what the
feed ore size for heap leaching should be.

This approach provides less scatter
than attempts to derive pre- and post-leach
assays of coarse size fractions from separate
samples.

Agglomeration, which can be more precisely
described as binding is desirable to
accommodate even modest quantities of fines
in ore intended for heap leaching.

Substances which bind mineral particles
are generally described as pozzolanas, and
usually form, when dampened, calcium
aluminate and silicate matrices which cement
fines together, over a period of 10 to 10^2
hours.

Agglomeration generally allows the permeability of clay-rich ores to be dramatically increased to provide a superficial leachate flux around 1m^3 leachate/m^2 heap surface per day.

Figure 2, drawn from information developed by Stroganov (1979), illustrates how the fraction of unagglomerated clay in an ore affects the superficial leachate flux. In practice clay fines are washed into lower levels, where they then constitute a greater fraction. This can lead to serious permeation problems, as is well illustrated in the paper by Chamberlin (1980).

In addition to the increased rate of leachate flux and thus rate of gold recovery resulting from agglomeration, agglomeration overcomes the dramatic (typically five-fold rate) loss in cash flow on scale-up demonstrated by Kappes (1981) on virtually all ore types as shown on figures 3 to 5.

This removal of the risk of scale-up by applying agglomeration is borne out by the excellent correspondence between small and fullscale operations which may be expected if agglomeration is applied, as shown in figures 6 and 7 (Houtgraaf, personal communication). (The corrections applied for leachate flux in these figures are motivated in the next section on Heap leaching).
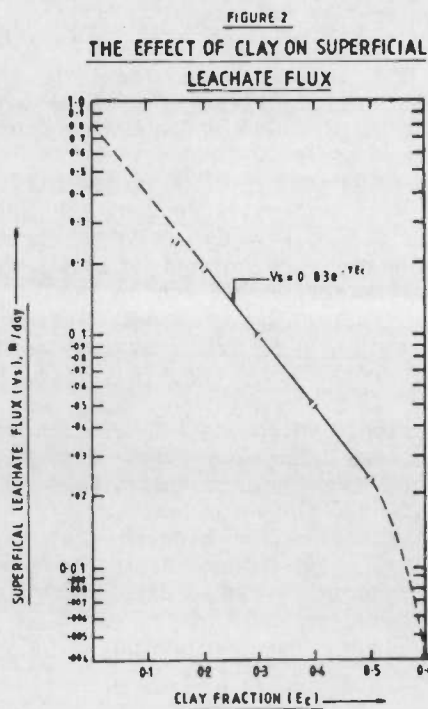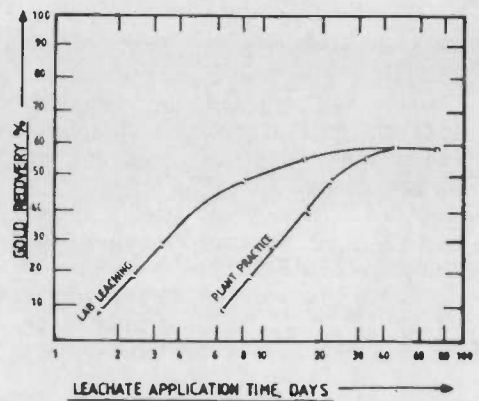
FIGURE 1

KAOLINITE

[UNAGGLOMERATED ORE]
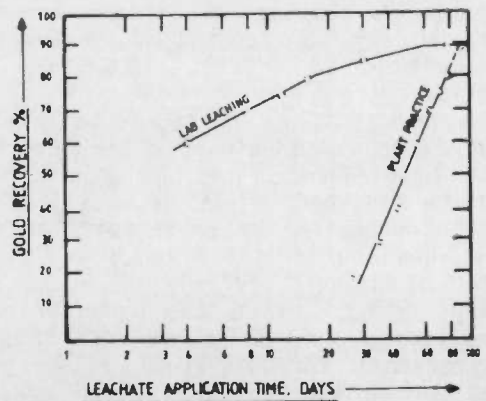
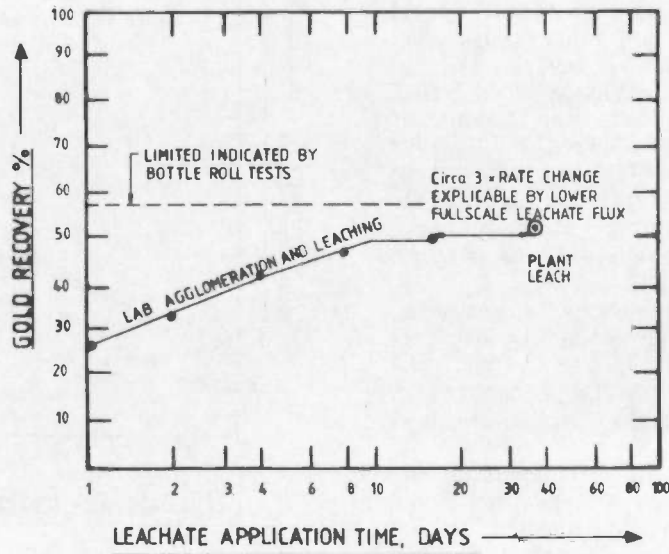FIGURE 4

LIMESTONE / SHALE

COLUMN TEST AND PLANT OPERATION

[UNAGGLOMERATED ORE]
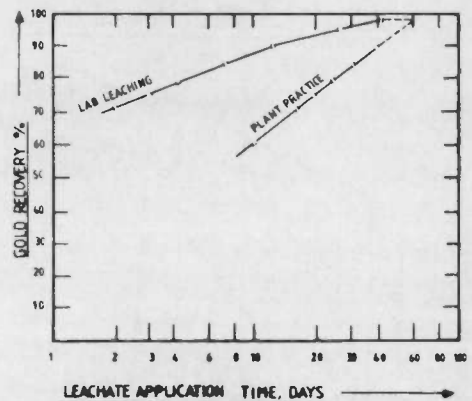
FIGURE 5

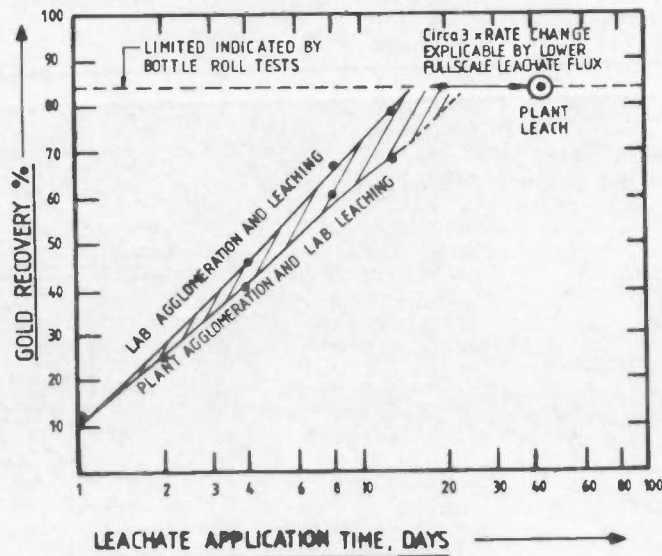CHERT / JASPEROID

COLUMN TEST AND PLANT OPERATION

[UNAGGLOMERATED ORE]

FIGURE 2

THE EFFECT OF CLAY ON SUPERFICIAL LEACHATE FLUX

$Vs = 0.03e^{-7Ec}$

FIGURE 6

"MABEL MILL"
COLUMN TEST AND PLANT OPERATION
[AGGLOMERATED ORE]

FIGURE 7

"OLD MAN"
COLUMN TEST AND PLANT OPERATION
[AGGLOMERATED ORE]

It should be noted that a patent for the agglomeration process as originally developed by the US Bureau of Mines has been applied for locally by Heinen et al. (1980). However this patent application is being opposed by some of the heavyweights in the local industry.

As the activities of many pozzolanas are known or easily assessed (e.g. it is known that lkg cement or 2kg fine flyash will bind approximately 30kg clay), it is generally possible to estimate how much pozzolan is needed to reduce the amount of free clay to a reasonable level. However since any remaining free clay may migrate to lower levels and form relatively impermeable pans which divert leachate, it may prove desirable to bind practically all the clay in taller heaps.
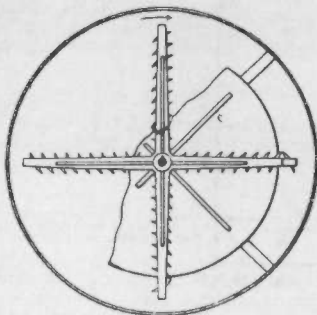
Many ores are inherently pozzolanic, and extrememly cheap pozzolanas such as flyash wastes may be available. Thus the amount of fines which may be economically bound can vary considerably for individual cases.

Where the cost of reagents for agglomeration is excessive, either the finer fraction or the entire ore needs to be treated by a slurry process. Where a coarser fraction of ore is removed, it will often be amenable to treatment by normal heap leaching, without further comminution, as gold mineralization is often concentrated near fracture planes. These options in fact cover the historic sand/slimes and all-slimes processes of gold recovery.

Pre-cyanidation of ore is generally desirable so that when solution is passed through the ore the major task of leachate is washing out dissolved gold rather than trying to get it into solution.
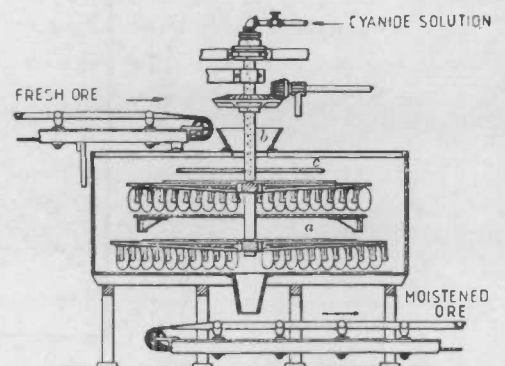
The effect of pre-cyanidation on cash-flow is dramatic, typically increasing it three-fold as shown on figure 8 (Houtgraaf, personal communication).

Although equipment was already developed to execute such so-called dry cyanidation by 1921 [see figure 9, reproduced from Julian and Smart (1921)] this process has been recently patented for ores finer than 1 mm by Balakrishnan and Skinner (1978).

FIGURE 8

"WILD IRISH GIRL"

COLUMN TEST AND PLANT OPERATION

[CYANIDE AGGLOMERATED ORE]

FIGURE 10

DRAIN COIL FITTED WITH FILTER SOCK

SIDE VIEW

FIGURE 9

BLAISDELL MIXER

FOR MOISTENING PULVERISED ORE
WITH CYANIDE SOLUTION

PLAN   ELEVATION
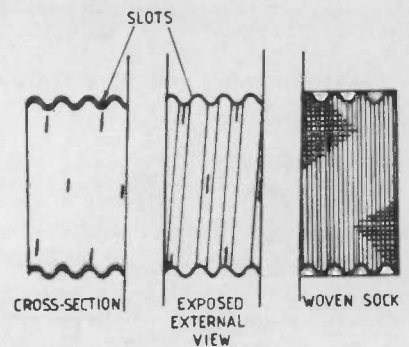
In agglomeration cyanidation, the effect of alkalinity and cyanide strength must be carefully considered and established by testwork to avoid excessive loss of costly cyanide and/or dissolution of undesired cations.

The exceptions where pre-cyanidation of ore is undesirable, occur if substances deleterious to the leach require their conversion or removal prior to the leach. Such deleterious substances are generally base, oxygen or cyanide consumers, such as

- unstable sulphides (e.g. pyrrhotite, realgar and orpiment) which may appear as the sulphide zone of an ore body is approached.
- ferric minerals common to ore zones near the watertable, and
- many copper minerals as listed in Table 1. The benefiication of copper-rich gold ores is however a vast subject and for heap leaching can become very complex as the copper cannot always be washed out prior to cyanidation. This subject will thus not be discussed here.

In conclusion I wish to note that particularly coherent base and top layers are generally desirable to respectively provide for stable drainage and to allow traffic for maintenance of irrigation equipment without excessive fines generation. Thus the development of practical heap building procedures to achieve such stratified heaps would be very useful. Higher cement dosages may thus be desirable for the critical top and bottom layers. Furthermore drain coils fitted with a filter sock as shown in figure 10 (Trichel, private communication) may be incorporated in the base of the heap.

FIGURE 11A

ALLIGATOR RIDGE
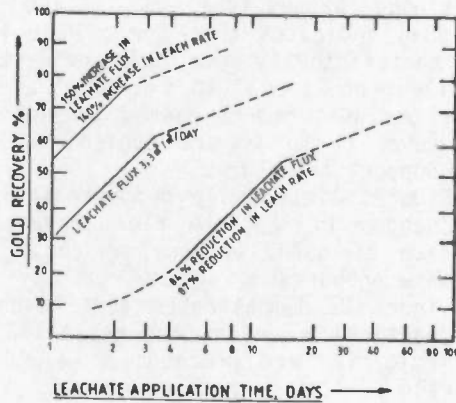COLUMN TEST
CYANIDE AGGLOMERATED ORE

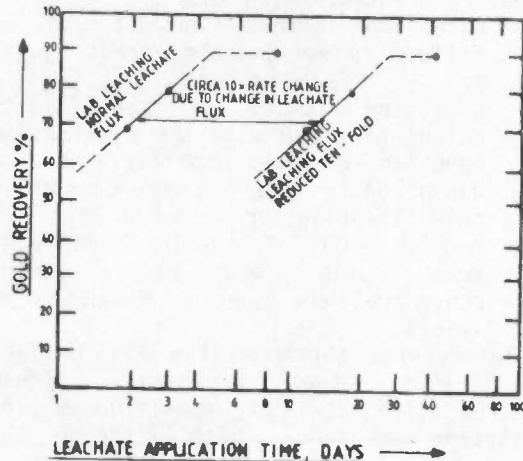FIGURE 11B
LIMESTONE
EFFECT OF LEACHATE FLUX
[UNAGGLOMERATED ORE]

TABLE 1: Cyanide reactivity of copper minerals (arranged in order of increasing reactivity)	
Unreactive minerals (10 $\pm$ 10% dissolves)	Reactive minerals (85 $\pm$ 10% dissolves)
Chalcopyrite $CuFeS_2$ Chrysocolla $CuSiO_3.2H_2O$ Tetrahedrite Cu_3SbS_3	Enargite Cu_3AsS_4 Bornite Cu_5FeS_4 Cuprite Cu_2O Native Copper Cu Chalcocite Cu_2S Malachite $CuCO_3.Cu(OH)_2$ Covellite CuS

HEAP OPERATION

"Recovery of gold proportional to cyanide exposure" is concluded to form a basic law of heap performance.

A considerable amount of test and operating data (Houtgraaf, personal communications; Kappes,1981; McClelland and Eisele, 1981) indicates that for a heap that operates satisfactorily the gold extraction is virtually proportional to the total amount of cyanide per unit of ore passed through the heap. Figures 11 to 14 are typical of the data that support this view:

- Figures 11a and 11b demonstrate that changes in leachate flux change the rate of gold recovery in about the same proportion.
- Figure 12 demonstrates that leaching practically ceases on cessation of irrigation and proceeds at a normal rate on recommencement of application of leachate.
- Figure 13 demonstrates that at a fixed leachate flux, the rate of leaching is closely related to the cyanide concentration.

Naturally other, more varied and obscure conclusions may be drawn from the treatment of ores suffering from

- excessive bypass because of a failure to agglomerate excess fines, or
- excessive levels of constituents which interfere with the cyanidation reaction or the stability of the dissolved gold complex after solubilization, or
- a high risk of cyanide loss e.g. from using very high cyanide concentrations and inadequate pH levels.

The results shown on fig 11a in fact suggest that the presumably fresh (non-leaching)leachate was depositing a slow precipitating substance which affected the extent of bypassing occurring within the heap.

Leachate distribution consitutes one of the most critical aspects of heap operation.

Except for vat leaching where flooded dams are created, irrigation equipment such as sprinklers are generally used to distribute leachate.

There is a strong case for using drip irrigation equipment as illustrated in figure 14c (Trichel, personal communication) to reduce evaporation and the erosion (particularly of side walls) resulting from droplet impact. The problem of attempting to achieve droplet size distributions which adequately balance such erosion with evaporation and mist losses can then also be avoided.

A further motivation for applying drip irrigation is that there is greater flexibility in the selection of pH and cyanide levels. The reduced exposure of leachate to air when applying drip rather than sprinkler irrigation allows more extreme limits of pH levels and cyanide concentration to be applied without necessarily increasing the consumption of cyanide excessively. This provides considerable operating flexibility as well as room for effectively reducing processing costs.

FIGURE 12

WILD IRISH GIRL
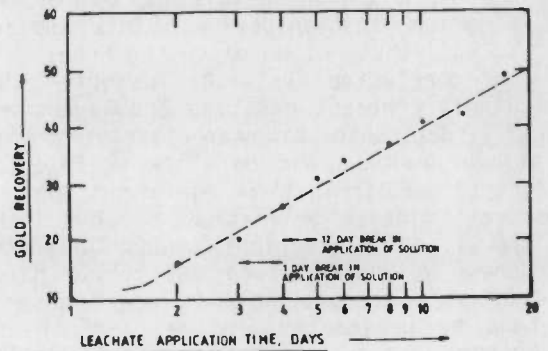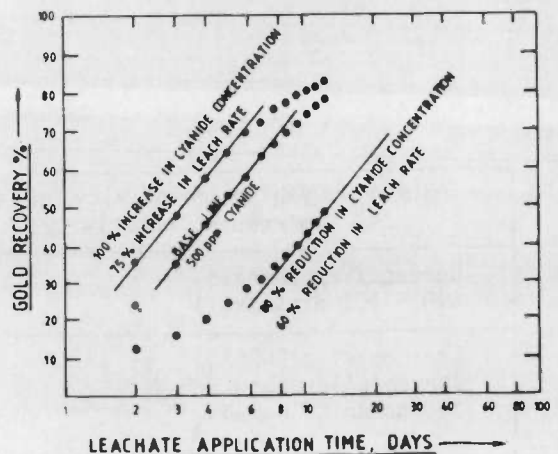## COLUMN TEST
(AGGLOMERATED ORE)

FIGURE 13

"OLD MAN"
COLUMN TEST
(AGGLOMERATED ORE)

Water quality management in heap leaching constitutes one of the most critical areas of heap operation. Interesting conflicts of chemistry, requiring innovative solutions for many heap leaching operations occur in this area.

In particular, cyanide associates with protons to form prussic acid at pH levels below 9,5. (Association is practically complete below pH 7,5). In contrast to cyanide, prussic acid is not very effective in leaching gold, and is furthermore easily lost by volatilization. However high calcium and carbonate levels are common in local water, furthermore bicarbonate commenses to dissociate to carbonate above pH 7,3, and is practically completely dissociated to carbonate above pH 9.3, and calcium carbonate is not very soluble.

Thus if one wishes to avoid the problems of reduced activity of cyanide for gold dissolution and also the potential for its loss as prussic acid vapours, one must accept the risk of calcium carbonate precipitation. (The precipitation of calcium salts particularly affects the effective continued operation of the irrigation equipment used to spread leachate over the heap, and also fouls the carbon commonly used to collect dissolved gold.)

A further complication in water management that arises in the treatment of many local weathered rocks is that magnesium released by weathering has not been washed out of the oxide ore because of the very arid conditions, and/or when such magnesium has been washed out, it has concentrated in the groundwaters which are most easily available for beneficiation of the ore.

Magnesium sets up a buffer in the pH range $8,8 \pm 0,3$ depending on magnesium concentration. If cyanide leaching is attempted in this pH range, increased cyanide dosages need to be applied to allow for loss of cyanide by vapourization. Thus either the magnesium must be precipitated prior to heap leaching, or drip rather than spray irrigation of leachate must be applied to reduce cyanide consumption.

Because of inter alia the low solubility of lime and the potential of insoluble precipitates on the surface of lime preventing the full utilization thereof, magnesium needs to be precipitated by NaOH rather than lime. Essentially all the magnesium can be precipitated with mere stochiometric quantities of caustic since the solubility product of $Mg(OH)_2$ at ambient is so low (about 10^{-11}).

Whether spray or drip irrigation is applied, the risk of precipitation of calcium salts (sulphates as well as carbonates) must

be eliminated. If no sulphates are present, the risk of calcium carbonate precipitation may be avoided by a modest reduction in pH after the bulk of the calcium has been precipitated by sodium carbonate. Sodium carbonate can remove calcium stochiometrically, since the solubility product of calcium carbonate is relatively low (around 10^{-8} to 10^{-9} depending on ambient temperature). However one must consider the influence of pH as the proton association constant for carbonate is fairly high (10^{10} to 10^{11} depending on ambient temperature).
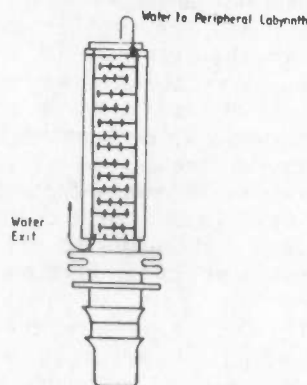
FIGURE 14
IRRIGATION DEVICES
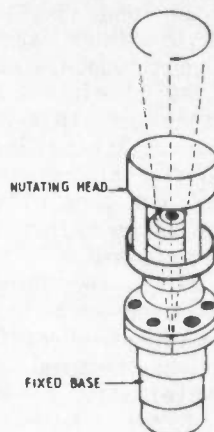
(a) THE SENNINGER WOBBLER ®
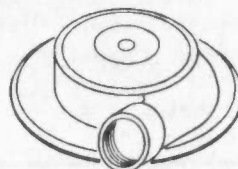
(b) STATIC FULL - CIRCLE SPRINKLER.

(c) EXPOSED VIEW OF LEACHATE FLOW PATH IN A LABYRINTH DRIPPER

Controlled precipitation must be executed where precipitation cannot be practically eliminated.

Sulphates, which are common in local ores derived from sulphide oxidation, present a particular water management problem as gypsum readily supersaturates, and can unexpectantly precipitate at a very high rate at favourable sites (e.g. those experiencing mechanical shock). Gypsum fouling is also not as easily removed (e.g. by a dilute acid wash) as calcium carbonate.

A successful approach to the control of calcium fouling (of activated carbon) which has been adopted by the Pinson Mine, Nevada, involves feeding calcium saturated waters to tailings, where many nucleation sites on the solids promote stripping off supersaturated fractions (Thorndycraft, personal communication). Duncan and Smolic (1977) record how Cortez Gold Mines successfully executed a similar conditioning step in a large barren pond at their Gold Acres operation. A variation of this technique applied in the Florida phosphate industry at the Bartow plant relies on the recycle of gypsum fines to seed and precipitate $CaSO_4$ as a fine powder in solution rather than as a troublesome solid on equipment.

Alternatively, after the bulk of the calcium has been removed e.g. by $CaCO_3$ precipitation, a significant quantity of the residual calcium may be removed either by sequestering or precipitation. Phosphates are generally applied for either of these processes. However polyphosphates used for sequestering generally have to be applied at three times stochiometric levels to remove the bulk of the calcium as the complexes formed are not particularly strong. This excess polyphosphate can disperse clays within the heap, causing permeability problems.

Simple phosphates are also dispersants, but since they can be practically stochiometrically reacted with calcium (the solubility product of $Ca_3(PO_4)_2$ is very low - about 10^{-32}), the problem of clay dispersion need not arise.

A final, and the most promising future technique for the control of precipitates (which is however at present more at the level of a Black art than a science), is magnetohydrodynamic water treatment.

By passing water at a significant velocity (around 10 m/s) through a strong magnetic field (over 3000 Gauss as now available from state-of-the-art permanent magnets) subsequent precipitation of calcium salts occurs as a slush rather than a cohesive build-up. I believe this is due to extensive seeding of crystals occurring in the magnetic field although there are arguments that the effect is due to a change in habit of existing seed crystals. However despite the great dispute over how magnetohydrodynamic water treatment works, it does seem to work.

A recent survey by Edward L Bateman (Barnea, personal communication), revealed about a dozen firms offering this technology and little basis for knowing how to select the equipment of one rather than the other. The only common feature appeared to be that all appeared to wish to price themselves out of the market.

FIGURE 15

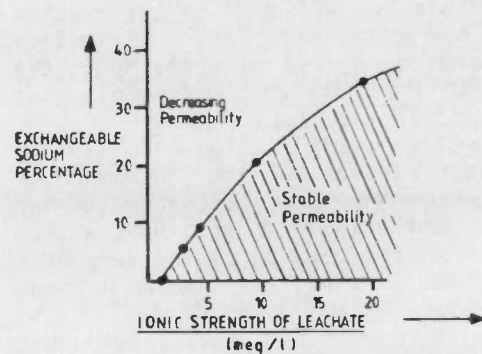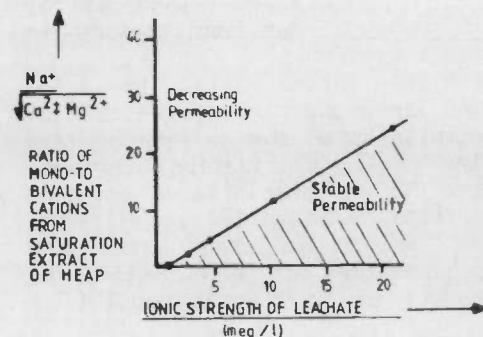# HEAP PERMEABILITY
IN RELATION TO ADSORPTION CHARACTERISTICS

FIGURE 16

HEAP PERMEABILITY OF NON-SODIC HEAPS
IN RELATION TO IONIC CHARACTERISTICS

Breakdown of colloid structure occurs if the ratio of dissolved alkali earth to alkali metals becomes too low e.g. as indicated by figures 15 and 16 (Quirk and Schofield, 1955; Quirk, 1971). If too much calcium and magnesium is precipitated colloid dispersion occurs and consequent heap permeability problems become inevitable.

This fact provides a good argument for the removal of essentially all the calcium and the retention of reasonable magnesium levels (and application of drip irrigation to contain losses of cyanide as prussic acid vapours), unless extensive agglomeration is applied.

Such an approach makes further sense if one considered the relatively low cost of Na_2CO_3 (needed to precipitate Ca) in comparison with 2NaOH (needed to precipitate Mg), and particularly so if one appreciates the feature of local groundwaters that levels of soluble calcium are typically an order of magnitude lower than soluble magnesium levels.

Most of the above problems of water management, precipitation control and breakdown of colloid structure are eliminated by applying an acid leach, and this provides a significant motivation to move away from alkali cyanidation to acid thiourea or chloride processing.

FIGURE 17
POURBAIX DIAGRAM

GOLD PRECIPITATION

Figure 17 demonstrates that gold can be precipitated out of aurocyanide solution to low tenor levels (as metal) by practically all commercial reductants at all pH levels, but more easily in acid solution.

Table 2 provides a brief summary of some gold precipitation processes which have been applied to date (Gmelin, 1954; Rose, 1906; Robine and Lenglen, 1906) and why some are no longer applied.

In general, the use of soluble reagents, and any need to manipulate pH to different levels for leaching and precipitation are not desirable in heap leaching because of the inherent buildup of such reagents which occurs following recycle of solution. In fact, the buildup of zinc (unless alkali conditioning be applied), is one of the main reasons why Merril precipitation is not generally desirable in a heap leach circuit. (The complexities introduced by

- dilution of precipitate by suspended solids which occurs if the feedstock is not clarified
- the desirability of deoxygenation, lead addition and absence of various base metals and
- the maintenance of a fair calcium level

to obtain good results, constitute further reasons).

Some very neat processes have been developed to handle the reagent build-up inherent in recycle operations, which could occur in heap leaching. As an example the cyanide recovery process of Crits (1981) uses Type II resins and simple elutions to separately recover zinc and recycle cyanide. However this general subject area of cyanide recovery is vast and cannot be adequately addressed in this paper.

The main gold precipitation processes that thus remain contenders for application in a heap leach circuit are electrowinning, either direct or following prior concentration by either carbon column or resin column adsorption and elution of aurocyanide.

Generally at the low solution tenors involved in heap leaching, film diffusion limits the rates at which gold can be electroplated. Any excess current is merely wasted on hydrogen production. Furthermore the increase in overvoltage as the gold tenor drops, and what appears to be some sort of back reaction (redissolution of dislodged gold flakes) appears to create a lower asymptotic gold recovery limit in the range of typical heap leachate tenors.
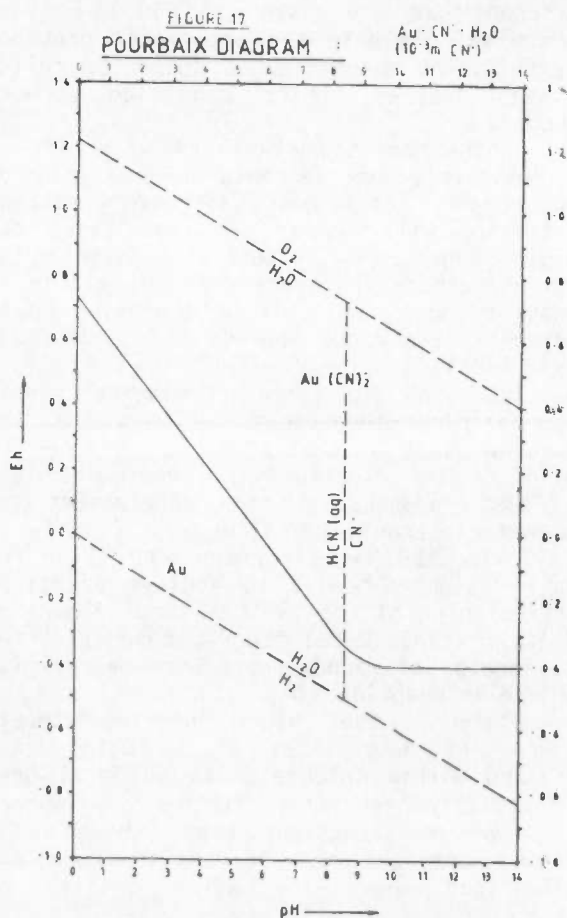
The abovementioned characteristics prevent the application of conventional electrowinning cell designs, and one or more of the following concepts must be incorporated to allow practical application of direct electrowinning of heap leachate:

- electrode scrubbing, where microturbulance greatly reduces the diffusion gradient/gold deposition barrier,
- staged (counter-current) heap leach operation to provide far greater leachate (electrolyte) tenors, and/or
- application of electrowinning residues to pre-treat ore in a pre-cyanidation and/or pre-agglomeration step. Any inefficiency in the cell performance is then of no major consequence as unrecovered *dissolved gold is* recycled right up to the last campaign. The liquors of the last campaign can then be stripped of gold in a single chemical precipitation or adsorption step.

A further desirable electrowinning feature is a large cathode surface to provide for a sufficient rate of gold deposition at the diffusion limit.

However before laying out money on a cell using poreous cathodes, one must be convinced that any given cell will in fact operate well despite the occasional presence of significant quantities of suspended solids in heap leaches, which can clog poreous cathodes.

Another point worth checking is if, at the relatively low leachate conductivity of some heap leachates, adequate cathode penetration will occur. In some cases the rapid drop in potential over the solution/cathode boundary deeper within a poreous cathode can limit gold plating to an inadequate outer zone nearest the anode (Paul et al. 1983).

The USBM has been developing staged heap leaching technology to increase the tenors of heap leachates and so reduce the demands on the electrowinning equipment, and are also addressing the development of improved electrowinning techniques (Eisele et al. 1984). ELB has also been addressing the detail design of cells to achieve practical electrowinning of the typical large flowrates and low precious metal tenors, conductivities and levels of anode-protective alkalinity involved in heap leaching.

However, the high chloride levels inherent to many local ground waters and contained within soluble salts in local ores will probably necessitate further development of anode construction even though the existing approach may be satisfactory for applications where the water quality is better.

TABLE 2: Precipitants which have been disclosed or used for the recovery of gold from cyanide solutions	
PRECIPITANT	RECORDED OR MOST LIKELY DEFECTS
Zinc	Efficiency is sensitive to the presence of base metals and dissolved oxygen.
Carbon	Low concentrations of deposited gold generally insufficient to avoid necessity to attempt recycling of carbon.
Cathodic Current	Efficiency and rate rapidly drops at lower tenors (except in cells which are yet not well proven commercially).
Cathodic Currents onto Amalgams	Low capacity, high cost, requires clarified solution to avoid slime-layer forming on amalgam
Cu-Zn Amalgam; Zinc-Amalgam	Cost, high residue tenors
Aluminium	Requires de-aeration and low Ca-levels
Silicon; Silicon/Alkali Earth Alloys	Cost
CuCl, H_2SO_4/CuCl/oxidant; H_2SO_4/Cu(I); SO_2/CuSO_4$	Cost
H_2SO_4/FeSO_4$	Cost
Alkaline hydrogen phosphide	Toxicity
Acetylene or carbide	Cost
Pb-salts	Cost
Hg plus Cu plus Zn-salts	Toxicity

Activated carbon allows simple and efficient capture of gold out of leachate, whereafter it may be eluted and electrowon from a more concentrated solution.

The first commercial process by which this was achieved was developed by Zadra, and his process has subsequently been modified in a number of ways including the use of organic additives and the application of higher temperatures.

AARL elution involves separation of the three steps of carbon pretreatment, carbon elution and eluate electrowinning . This allows considerable flexibility in optimising each step and provides a number of other advantages over Zadra elution as outlined in table 3. A more complete paper on this subject is available on request from ELB.

The Micron Research elution technology has been locally developed and is thus fairly well known here. At the time of writing it appears that early problems apparently related to engineering rather than any fundamental flaw in the process have been overcome and two commercial units are said to be behaving satisfactorily in commissioning trials (at Tower Hill and Edjujina). However insufficient information is yet available at the time of writing this paper on the longer term performance of carbon eluted by this process and the extent to which regeneration may be dispensed with, to allow a fair assessment of this technology to be made at this stage.

Fleming and Cromberge (1984a, 1984b, 1984c) have provided information which indicates that high pKa weak-base resins may supercede carbon as an adsorbent to recover cyanide-leached gold.

In brief, resins are far less prone to fouling, and a small quantity of very strong electrolyte ideally suited for electrowinning is easily and rapidly generated from loaded resin by a simple caustic wash.

A high pKa is desirable to avoid the need for acidulation prior to adsorption and subsequent neutralization prior to recycle of leachate.

Although electrowinning of the relatively strong electrolytes produced by this process can be processed in cells of virtually any design, the use of a design which incorporates a parallel fluid and current flux as illustrated by Surfleet and Crowle (1972) and relatively thin cathodes is desirable because of the high gold loadings per unit of steel wool which can be achieved in this type of cell provided conditions are selected to avoid inactive zone in the cathode.

Such high loadings allow practical direct smelting of · cathodes without the necessity of attempting prior acid washing of the steel wool, which is after all gold plated and thus protected against the very attack being attempted.

The electrowinning of gold onto aluminium foil and the alkali dissolution of the foil to produce bullion flake, as developed by Arnold Griffin is an attractive alternative, particularly where smaller quantities of electrolyte are involved.

BULLION PRODUCTION

Smelting constitutes one of the more obscure areas related to heap leach operation. A great variety of practices are applied, few rationally developed and optimized and most reminding one of medieval alchemy.

TABLE 3: The relative merits of AARL and Zadra elution.

The AARL system

-       is cheaper with respect to operating costs

-       is more flexible to handling changes in feedstock or increases in contaminants in feedstock

-       is less sensitive to temperature fluctuation occurring during elution, and contaminants returned by recycling of eluate

-       is faster

-       limits kiln degradation

The Zadra system

-       can more readily accommodate poor quality of water used to make up eluate

-       is tolerant of unoptimized electrowinning call design

-       is simpler where no sequence control may be applied.

Because of the practical importance of smelting in heap leaching operations, this subject has been addressed fairly extensively in a paper which is available on request from ELB. This paper also discusses the best crucible, kiln and fuel for smelting steelwool cathodes to recover dore bullion under typical local conditions. Table 4 summarizes a set of good flux recipes derived in this paper. Potassium rather than sodium has lately been specified for the nitrate because of its superior thermal stability.

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TABLE 4:	Recipes useful in direct smelting of steel wool cathodes	
a)	Flux per kg Fe.	2 kg $NaNO_3$ 1,4 kg SiO_2 1,3 kg $Na_2B_4O_2 \cdot 10H_2O$
b)	Flux per mole of base metal (generally Cu) to be removed from doré	1 mole SiO_2 0,2 moles $Na_2B_4O_7 \cdot 10H_2O$
c)	Flux for additional in-situ oxidation (dull or sticky slag; low fineness; brassy, hard or magnetic doré).	55% $NaNO_3$ 45% SiO_2

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