MAXIMISING THE VALUE DERIVED FROM LABORATORY TESTWORK TOWARDS HEAP LEACHING DESIGN

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Abstract

Heap leaching can be considered for a wide range of ore and mineral types, and the design and operation of heap leach plants have continued to be adapted and refined towards optimization and towards meeting the requirements of increasingly challenging applications. For heap leach testwork, coarsely crushed aggregate is required, which dictates that underground resources must be sampled by obtaining relatively expensive diamond drill cores that can be crushed to a range of sizes typically between 6 and 50 mm. Every attempt should therefore be made to extract the maximum information from these expensive samples. It is common laboratory practice to perform chemical, mineralogical and physical characterization of the ore, followed by bottle and column leach tests. But several possibilities exist for extracting much more than this basic information from the ore samples, before reverting to pilot or demonstration plant studies. For example, geochemical modeling coupled to the mineralogical information can be used to extrapolate better quality estimates of the acid consumption, the formation of in-heap precipitates and (from integrated flowsheet simulations) the composition of the feed to metals recovery on the ultimate commercial scale plant. Furthermore, in the case of sulfidic ores, oxygen uptake measurements over the laboratory leach columns can be used to infer the rates of chemical reaction and heat generation. These rates allow the development of the vertical temperature profile with time to be calculated, which can be applied to the heating jackets of the columns to better simulate commercial-scale high-temperature heap leaching. Further insight into the factors limiting the process kinetics at any given temporal or spatial point could be gained by studying the bacterial populations obtained from such columns, which may suggest further means of process optimization. Comment is made on the effect of inoculation during heap bioleaching applications, and on the combination of inoculation and agglomeration of ore destined for heap bioleaching. During column leach experiments on uranium ores, a bacterially inoculated column ought to be included to verify the effect on operating cost of bacterial acid generation and bacterial ferrous iron oxidation throughout a heap. A case study is provided of how the results from batch column tests, coupled with flowsheet calculations, were used to optimize the acid balance of a counter-current laterite heap leach and downstream recovery process.

Introduction

The remaining minerals resources of the world are gradually becoming more challenging to exploit by the conventional processing technologies. As a result, ongoing innovation is called for to provide economically feasible technologies, while also placing greater emphasis on minimizing the impact on the immediate and the global environment over the life of a project and after decommissioning.

Incremental innovation is continuously taking place in heap leaching (as it is no doubt occurring in other technologies), but may not be very visible since most of it does not involve entirely new process routes or novel reagents. Rather, it mostly involves such aspects as more detailed attention to the mineralogical, chemical and physical characterisation of the feed material, more complex mine management and ore preparation routes (although it still draws on existing technologies), more intensive instrumentation and automation and/or more restrictive boundaries to the operating parameters.

This could require a larger number of processing parameters to be defined during the testwork program, and for a particularly challenging ore type the window of feasible parameters that the testwork program is attempting to identify may be quite narrow. However the number of column leach tests that can be performed to define these parameters are limited since, for heap leaching testwork, relatively large amounts of diamond drill core sample are required, which are more expensive to obtain than reverse-circulation drilling samples. It is therefore essential that the maximum scope of information is derived from the sample provided.

Certain aspects of heap leaching design have been quite extensively implemented commercially with little fundamental understanding. One such area that still requires investigation is the management of bacteria in sulfide ore heap leaching, where one reason for the scant attention being paid to it has been a lack of techniques for analyzing bacteria on solid surfaces. Efforts are being made to obtain more quantifiable information on bacterial performance during metallurgical test programs, and to be able to provide guidelines for its active management together with the other heap leach control actions.

This paper deals with a number of aspects that should be included in a metallurgical testwork program aimed at the heap leaching of an ore, and particularly of the more challenging ore types, to maximize the value derived from metallurgical testwork.

Mineralogical

Ore and gangue mineralogy is fundamental to the metallurgical behaviour, and therefore to the technical and economic amenability of an ore to exploitation. Apparently minor changes in gangue mineralogy can have a significant impact on the requirements for acid curing and agglomeration prior to heap leaching, and on the acid consumption, metal extraction, and Pregnant Leach Solution (PLS) chemistry during leaching.

Certain gangue minerals like calcite ($CaCO_3$) are very reactive to acid and will in time dissolve completely in contact with even very dilute sulfuric acid solutions. Ores that contain a significant proportion of such minerals will be clearly unsuitable for acidic heap leaching. However more commonly silicate minerals constitute the most significant acid consuming component of the ore. Silicates form a group of inorganic compounds of great chemical and structural complexity, and they occur in all groups of rocks.

The silicate minerals react incompletely with sulfuric acid and with several of them the extent of acid-gangue reaction is a function of the acid strength in the leach liquor. The moderate reactivity to acid of these gangue minerals limits their acid consumption sufficiently that acid heap leaching of the ore can be economically viable with relatively low valuable metal grade. It therefore leaves a margin of control over the acid consumption, and permits an economic optimum to be sought between acid cost and leach kinetics, by varying the acid curing parameters and the acidity of the irrigation liquor in a matrix of metallurgical tests.

This further implies that, from an understanding of the reactions between particularly the silicate gangue minerals and sulfuric acid, it is possible to make predictions about the likely acid consumption of the ore under various conditions of irrigation acid strength, and from that can follow predictions about the precipitates that are likely to form inside the heap, as well as the (both valuable and nuisance) soluble species that are likely to report to the pregnant leach liquor feeding the downstream recovery steps. Such predictions can already start to be made during the earliest phase of a project, when only a limited amount of drill core sample may be available, based on a knowledge of the gangue mineralogy, coupled to geochemical database information and modelling software.

Temperature is a another important parameter to consider in gangue reactions, which is becoming very relevant to efforts to do high temperature heap leaching, in that it should be ensured that the extraction benefit realised by the increased heap temperature is not countered by the concomitant increase in acid consumption.

A further level of sophistication that is being strived towards is to be able to use laboratory-scale experiments (like rolling bottle tests) to provide quantitative inputs to mathematical models and databases of various possible levels of sophistication to simulate a commercial heap leach operation with regard to acid consumption and drainage composition. This level of interpretation is usually delayed until only much later in the project when tall column leach or pilot plant experiments are undertaken. However, such information would be very valuable to have even after the earliest stage of exploration, at which time there is often insufficient drill core sample material available for column leach tests.

Physical

The particle size distribution of an ore is obviously always an important parameter for heap leach process design. By performing this very basic procedure both dry and wet (after soaking) and comparing the two results, more valuable information is obtained than by merely doing it either wet or dry. For example, with uranium-bearing mudstone, the wet screen size analysis can typically be shifted considerably towards the smaller screen sizes, compared to the dry screen analysis, as shown in Figure 1.

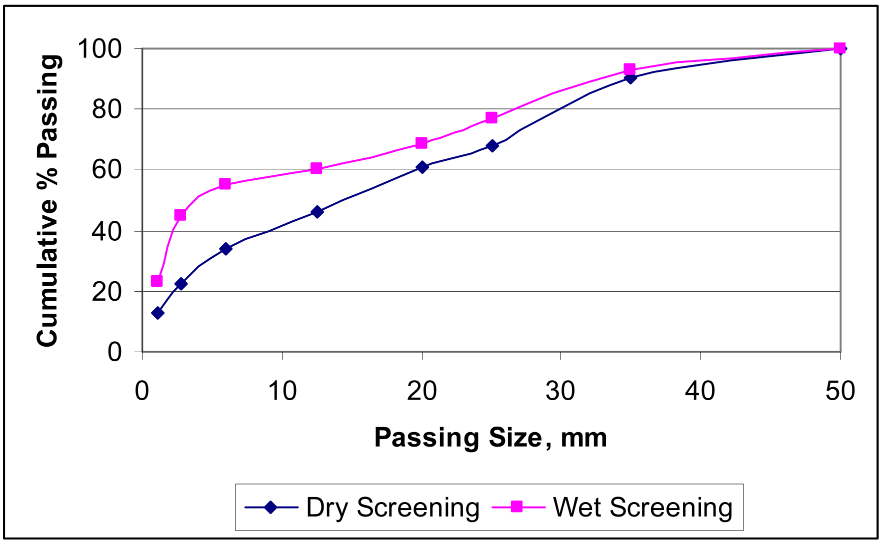

Figure 1. Comparison of Wet and Dry Screen Size Analysis of <50mm Mudstone

This is due to hard lumps of fines which quickly decompose to their constituent fines upon wetting, and which can hinder percolation should these lumps be stacked on a heap. For severe cases a form of scrubbing needs to be considered prior to agglomeration to evenly distribute the finer and coarser particles.

If the finer size fractions are considerably upgraded in the valuable metal compared to the coarser particles, it may be possible to screen or classify the ore into two streams, where the finer fraction could be agitation-leached in tanks while the coarser fraction is heap leached, or even discarded.

A set of geo-mechanical and ore hydrology tests is required to provide systematic data on such parameters as:

- ore bulk density vs. stacked heap height
- air and hydraulic permeability
- moisture hold-up versus application rate.

The above parameters can also be derived during the course of the normal column leach tests, but a dedicated set of geo-mechanical tests can provide many more data points than can practically be achieved with column leach tests. It provides a quantifiable indication of the optimal stacking height and irrigation rate from the geo-mechanical point of view (or operating regimes that should be avoided). It therefore defines restrictions within which column leach parameters such as maximum stacking height and maximum irrigation rate should be varied.

Extractive Metallurgical

The extractive metallurgy is obviously central to the testwork program, and aims to determine whether the valuable metal can be extracted from an ore, and if so, under which conditions, at what rate and at what reagent cost.

The matrix of possible heap leaching operating parameters include

a. nominal crush size
b. reagent concentration in the leach solution
c. effect of temperature
d. requirement or not for maintaining oxidizing conditions.
e. requirement or not for agglomeration and if so, with or without binder addition
f. optimal stacking height
g. irrigation rate.

Rolling bottle leach tests are typically performed to narrow the feasible ranges regarding parameters a. to d. above, since they require small amounts of sample and are of short duration. Poor extraction results under all rolling bottle test conditions would suggest that atmospheric leaching (including heap leaching) is not a feasible processing route. However with most ore types it is not possible to draw firm conclusions from the reagent consumption figures observed during rolling bottle tests. The reagent consumption figures obtained from rolling bottle tests (where the solids are suspended in leach liquor) are usually considerably over-stated compared to what can be expected under the percolation leaching conditions of a column or a heap. Rolling bottle leach results indicate the maximum final extractions achievable under the selected conditions, but they do not provide quantitative kinetic information for heap leach design.

Column tests can then be performed on the now narrowed range of parameters a. to d., to explore the suitable or near-optimal range for parameters e. to g. Column leach experiments yield much improved estimates of the reagent consumption and when conducted at the intended heap stacking height, they provide kinetic information that can be applied to heap leach process design. Column leach experiments in closed circuit with a metal recovery step (and with a bleed as appropriate) can simulate the anticipated accumulation of chemical species in solution, and such solution samples can be used for detailed downstream purification and metals recovery testwork.

Environmental

At least one column test should be dedicated to be continued for another couple of months after the completion of leaching, to study the chemical composition of the drainage solutions emanating from it over time, for the purpose of the environmental impact study. For the most conservative observations, the column should be aerated during this time, and an irrigation program simulating the local rate of precipitation should be used. It can also be instructive the obtain solid samples from the column during the test, to observe changes in the metals and gangue mineralogy, to be reconciled with the observations made on the drainage solutions.

The fresh ore, as well as ore obtained from the column after various extents of leaching, should also be characterized in terms of established parameters for acid generation/neutralization potential, such as the ANC (acid neutralization capacity) and NAG (net acid generation). However, care should be exercised in the interpretation of the numbers obtained, since the conditions employed in some of the standardized procedures may render the results meaningless with respect to the heap leach application under study.

Microbiological

Characterisation

Microbial activity is required in heaps where oxidative leaching of sulfide minerals is required, as is currently practiced in the heap bioleaching of low-grade chalcocite ores. The utilization of micro-organisms for the in-heap generation of acid from sulfur, or the generation of organic acids, could also be considered. This aspect is commented on further in the last section of this paper.

While base metal heap bioleaching is well established world-wide, the microbiology of heap bioleach processes is still poorly understood. It is accepted that differences in parameters such as temperature, pH and aeration in different parts of the heap and at different times of the heap lifetime could have an effect on the populations present.

Until a few years ago, direct microbial counts and indirect measurements such as oxygen uptake rates, redox potential, pH, ferrous iron concentration and temperature have been used as an indication of the bulk activity of micro-organisms in the heap. In addition, microbial enrichments from solutions and ores have provided an initial view of microorganisms associated with the process. It was, however, not known whether these cultured strains were the key players in the process(1,2). The development of new culture-independent molecular techniques, such as polymerase chain reaction (PCR), denaturing gradient gel electrophoresis (DGGE) and fluorescent *in situ* hybridization (FISH), to detect and quantify populations, is a significant advancement and is a valuable tool in accurately describing biodiversity and following changes in microbial consortia present in bioleaching systems(2,3,4).

There have, however, been relatively few studies on the microbiology of heap leach systems and most of these have analyzed the liquid phases i.e. pregnant leach solutions and raffinate(5). Since the micro-organisms are not only present in the liquid fraction, but also attached to the ores surfaces, it is important to include the attached population when assessing the microbial composition within the heap.

Molecular techniques, such as quantitative PCR, which will allow the identification and quantification of microbes in heap bioleach processes, are being developed at Mintek. It is envisaged that the ability to correlate microbial types and numbers to changes in the chemical and physical profile with time in the heap, would assist in solving process issues such as how a heap should be inoculated, which microbial cultures to add and when to inoculate. It could potentially be a step towards optimizing rates, achieving faster start-up and better metal extractions.

Inoculation

For the heap bioleaching of sulfide ores, a prerequisite for successful processing is the establishment in the heap of a viable culture of suitable bacteria (i.e. inoculation of the heap). Various mechanisms for achieving this can be considered, such as

- spraying a bacterial-rich solution into the agglomerator
- spraying a bacterial-rich solution onto the ore during stacking
- irrigating the heap, after stacking, with a bacterial-rich solution.

During a testwork campaign, an indication ought to be obtained of the effectiveness of either procedure, with respect to such parameters as (a) bacterial survival rate, (b) lag time required to achieve a measurable oxygen uptake rate.

With the advent of high-temperature heap bioleaching(6), the choice of inoculation procedure is complicated by the fact that the heap conditions correspond to the operating ranges of different cultures at different time periods, which require more than one stage of inoculation. The most suitable procedure for each stage of inoculation therefore needs to be identified during experimental testwork.

Inoculation of a heap by irrigation over the top surface could normally not be expected to be the most effective method, because bioleach bacteria are naturally adhesive; they attach to the ore surfaces within the first few centimeters and are therefore slow to penetrate the depths of the heap(7). Techniques for modifying and quantifying bacterial adhesiveness have therefore been developed. Gericke et. al.(7) describe a process whereby bacteria can be prepared in a non-adhesive form, so that they can penetrate the heap. Bacteria can lose their adhesive qualities by, for example, being deprived of an essential nutrient. Once in the heap, the application of the missing nutrient will restore normal adhesiveness, resulting in an active and healthy population within the heap. To the knowledge of the authors this procedure has not been applied commercially, but would be a concept to consider particularly for applications where more than one phase of inoculation may be required, and where therefore at least one of the inoculation steps would need to be conducted after the ore has been stacked.

Case Study: Flowsheeting and Economic Optimisation

Background

Testwork towards the counter-current acid heap leaching of nickel laterite ores provides a case study for the utilization of column leach results to arrive at a conceptual flowsheet and optimisation of the acid balance.

Laterites are generally classified into limonite, nontronite and saprolite mineralogy, although these may occur to varying degree in each deposit. Limonites consist of iron oxy-hydroxides such as goethite and hematite (typically Fe >40%, MgO < 5%) and are suitable for pressure leaching. The limonite fraction responds poorly to atmospheric heap leaching and also generates high levels of iron in the leach solution. During pressure leaching, acid is regenerated from iron hydrolysis. Nontronites consist of smectite clays (typically Fe 25-40%, MgO 5-15%) and should generally be more suitable to the Caron (ammonia-leach) process. Nontronites also yield favorable kinetics under atmospheric leach conditions, but the presence of clays may cause permeability problems during heap leaching.

Saprolites consist of hydrated Mg-Ni silicates such as garnierite and serpentine (typically MgO 15-35%, Fe 10-25%) and are suitable for atmospheric tank leaching, heap leaching or smelting(8). The saprolite fraction also has better heap leach permeability.

Due to the high acid consumption associated with laterite heap leaching (typically 500-700kg/t), a low-cost acid source and/or on-site acid plant is required for economic and logistic feasibility. For a plant with high infrastructure requirements, the capital cost of the leach plant is not a significant percentage of the overall capital cost, which favors a somewhat more expensive agitated leach plant to achieve higher leach efficiency. Heap leaching of laterites is suitable for a small resource with smaller infrastructural requirements, or for a brownfield expansion such as Murrin Murrin. For example, a saprolite heap can be used to neutralize the leach solution exiting a pressure leach plant processing a limonite fraction.

For a stand-alone process, an intermediate precipitate such as nickel hydroxide is normally produced as end product, as opposed to nickel cathode. But in either event, complete acid neutralization and iron removal from the leach liquor is required prior to the nickel product recovery.

During the atmospheric heap leaching of laterites, the leach rate is directly proportional to the rate at which acid is supplied to the ore, which is a function of (a) the irrigation acid concentration and (b) the irrigation rate. A number of 1-m and 6-m column tests performed on individual laterite minerals and composites, using different irrigation acid concentrations, yielded similar linear behavior of nickel recovery versus acid consumption, as plotted in the Figure 2 below.

On many other types of ores, it is found that with increasing lixiviant concentration, the extraction kinetics do increase, but the ratio of metal extraction to reagent consumption becomes less favorable. This is not the case with laterite leaching, since complete nickel extraction relies on complete digestion of what could be termed the “nickel-bearing gangue”, and there does not exist room for optimisation of acid consumption versus nickel extraction in the leach section. (However as shown below, the acid balance can be optimized over the global process flowsheet).

The rate of nickel extraction during heap leaching may therefore be increased by using higher acid concentrations and/or faster irrigation rates while maintaining the same ratio of kg metal extracted per kg reagent consumed. The irrigation rate is limited by the permeability of the material, and the acid strength is limited by the need to minimize residual acid in the pregnant leach solution (PLS) reporting to the recovery plant. Residual acid in the PLS requires neutralizing agent addition in the recovery plant, which in turn leads to additional acid make-up required in the leach plant.

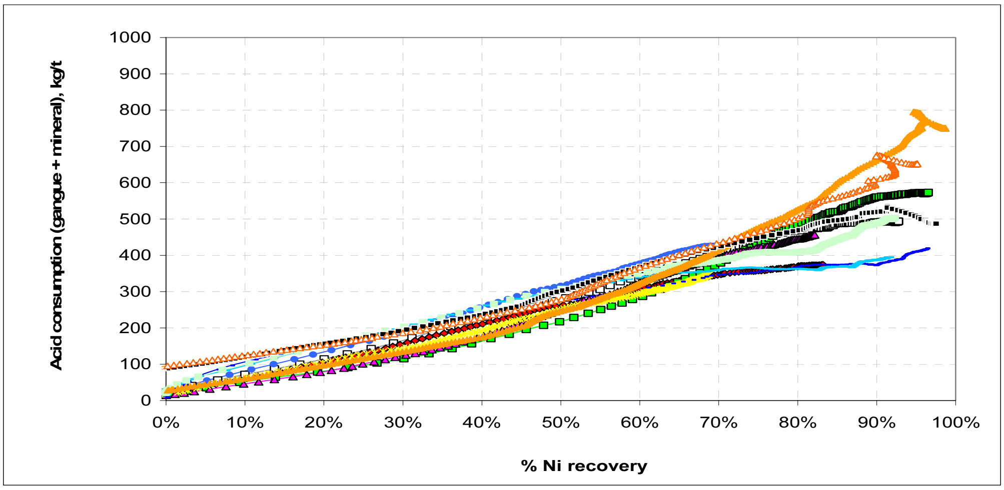

Figure 2. Linear Relationship Between Acid Consumption and Nickel Extraction (Using irrigation acid concentrations between 75 and 150 g/L)

Optimisation With Regard to Acid Consumption

An advantage of laterite heap leaching over agitated leaching is the absence of a liquid-solid separation step, which makes counter-current operation relatively simple. In order to achieve the maximum nickel leach kinetics from high irrigation acid concentration, while at the same time minimizing the residual acid reporting to the purification plant, a counter-current heap leaching flowsheet is utilized, as illustrated in Figure 3.

The following definitions and conventions are required:

- Heaps are regarded as “new” while (virtually) no acid is present in their drainage liquor.
- Heaps are regarded as “old” once the acid front is breaking through in the drainage liquor.
- A heap is regarded as “spent”, to be rinsed and discarded, once the rate of nickel extraction from it drops below an economic threshold.

- The inventory of ore being processed is divided into a convenient and practical number of discreet heaps, as a first iteration for the example below, five “old” and one “new” heap was assumed as shown in Figure 3.

- It is intended to maintain the maximum irrigation rate over all heaps at all times, and assuming that the permeability of all heaps remain equal, the irrigation rate over all heaps will therefore always be the same.
- It follows from the above that the time period during which a heap is regarded as "new" should be one sixth of the total leaching time period, that is from starting as "new" up to being "spent".

"New" heaps are irrigated with intermediate leach solution (ILS), which is bled from the combined drainage of the "old" heaps. The acid strength in the ILS should ideally be the maximum that can be completely neutralized over the "new" heaps during one sixth of the total leach time. This will depend on the neutralizing capacity of the fresh ore material, which is a function of the ore mineralogy, and of the height of the heaps. (Saprolite and nontronites normally have high acid neutralizing capacity, but limonites have poor neutralizing capacity).

The leach solution draining from the "old" heaps is collected in the Irrigation Pond where it is re-acidified prior to irrigation over the "old" heaps, to the extent that the combined drainage from the "old" heaps ideally contains the acid concentration required for the irrigation of the "new" heap.

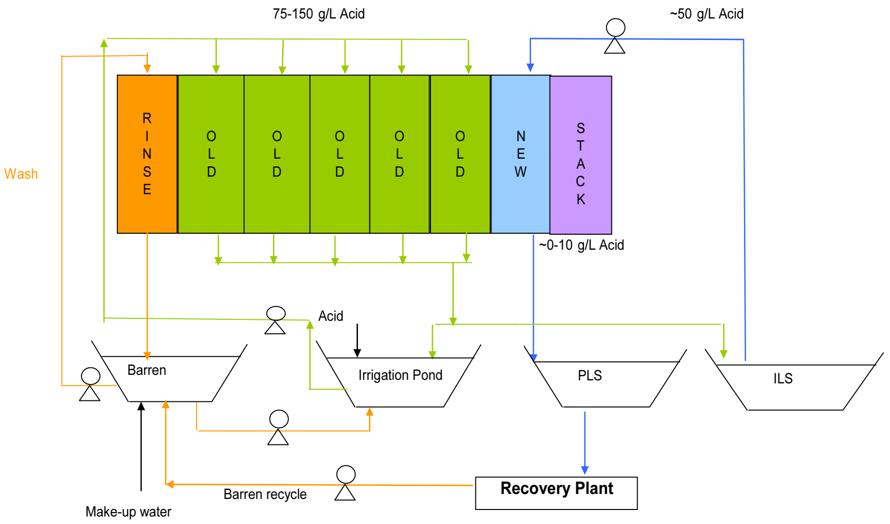

Figure 3. Conceptual Laterite Heap Leach Process

The acid concentrations observed in the irrigation and drainage liquors of 6m column tests are shown in Figure 4. Using 50 g/l acid to irrigate the fresh material, acid break-through started to appear in 70 days. Based on the assumption of one "new" and five "old" heaps, a leach time as a "new" heap of 70 days implies a total leach time of 6 x 70 = 420 days.

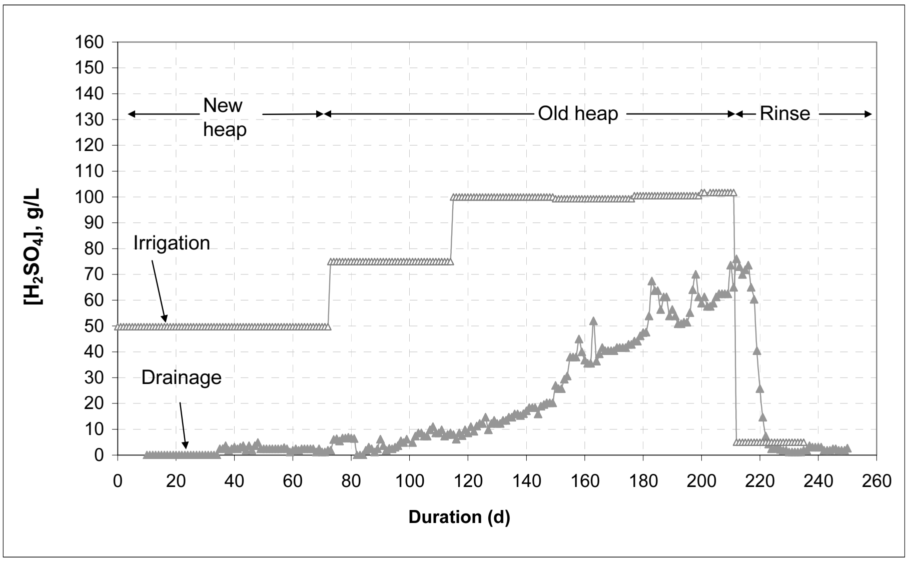

Figure 4. Acid Concentrations During Laterite Leaching in 6 meter Columns

From day 70 onward, the 6m column (now being regarded as "old") was further irrigated first with 75 g/l acid and later with 100 g/l acid, in an attempt to yield drainage liquor bearing an average of 50 g/l acid between the 70 days mark and completion of leaching.

It was ultimately found that nickel extraction had been completed after 210 days, and between 70 and 210 days (i.e. the period of being an "old" heap) an average of 40 g/l acid occurred in the drainage. The total leach period was therefore much shorter than the initially envisaged 420 days mentioned above, and leaves a few possibilities for a subsequent iteration for further optimisation and improved convergence of the acid and nickel balances. One option would be:

- Accept a total leach duration of 210 days,
- But with one "new" heap and only two "old" heaps (i.e. a total of three heaps), each with a leach duration of 70 days.
- The combined drainage liquors from the "old" heaps would yield an average of only 40 g/l acid, hence another 10 g/l acid addition would be required to the ILS pond.

A disadvantage of such an option would be that the acid concentration in the combined drainage liquors of only two "old" heaps would fluctuate more severely than it would in the combined drainage liquors of a larger number of heaps.

Another option would therefore be:

- Retain the total leach duration of 210 days.
- But start the irrigation of a "new" heap using 100 g/l acid (instead of 50 g/l), by using a larger acid addition to the ILS pond, to reduce the leach duration of a "new" heap from 70 days to an expected 35 days. (The larger acid addition to the ILS pond does not constitute an additional acid cost, it merely shifts a greater proportion of the total acid addition from the Irrigation Pond to the ILS pond).
- Now, with a leach duration of 35 days per heap and a total leach duration of 210 days, there would have to be five "old" heaps, to yield a total of six heaps, so that 6 x 35 days = 210 days total.
- Each of these six heaps would contain half the tonnage that would be contained in each heap if there were a total of only three heaps.

Possible Further Optimisation

In addition to chemical acid leaching, there are also two potential routes for the bioleaching of laterites namely:

(1) In order to save on the capital cost of an acid plant, elemental sulfur may be mixed in with the ore during agglomeration, and sulfuric acid may be generated bacterially within the heaps. Evidence from past heap leaching testwork has shown that bacteria can generate and tolerate up to around 70 g/l acid produced from commercial-grade pelletized sulfur added to the heap. This approach has however not been demonstrated or optimized in large-scale piloting or commercial scale applications. There may be a capital cost saving from not building an acid plant, on the other hand the cost of sulfur could be the same or even higher if the sulfur utilization is poor.

(2) Fungi has been used to generate organic acids (citric, oxalic) from a carbon source such as molasses and nickel recovery from laterites of up to 60% has been reported(9, 10). However, an experimental testwork program aimed at evaluating such a process should investigate the cost of the organic carbon source that would be required, and whether inexpensive organic waste products could be used for that purpose. Furthermore, when evaluating a biological process that relies on the selective growth of preferred organisms, the effect of contamination by other species in an open environment should also be investigated.

Conclusions

The remaining minerals resources of the world are gradually becoming more challenging to exploit by the conventional processing technologies. Incremental innovation is therefore occurring in heap leaching (as in other processes) to exploit the more challenging ore resources, which requires an ever growing number of processing parameters to be defined during the metallurgical testwork program.

For heap leaching testwork, relatively large amounts of relatively expensive diamond drill core sample are required, and it is therefore essential that the metallurgical test program is designed to yield the maximum scope of information from the sample provided.

Examples of specific tests and procedures that should be included in a metallurgical heap leach test program for a challenging ore type can be summarized as follows.

- Mineralogy

From an understanding of the reactions between particularly the silicate gangue minerals and sulfuric acid, it is possible to make predictions about the likely acid consumption of the ore under various conditions of irrigation acid strength, and from that can follow predictions about the (both valuable and nuisance) soluble species that are likely to report to the pregnant leach liquor feeding the downstream recovery steps.

A further level of sophistication that is being strived towards is to be able to use laboratory-scale experiments (like rolling bottle tests), coupled to mathematical models to simulate a commercial heap leach operation with regard to acid consumption and drainage composition, at the early stage of a project where the available drill core sample may not be sufficient for column leach experiments.

- Physical

From a comparison of dry and wet screen size analysis, and chemical analysis of individual screen sizes, a need for scrubbing prior to agglomeration may be identified. If the finer size fractions are considerably upgraded in the valuable metal compared to the coarser particles, it may be possible to screen or classify the ore into two streams, where the finer fraction could be agitation-leached in tanks while the coarser fraction is heap leached, or even discarded.

A set of geo-mechanical and ore hydrology tests is required to provide a quantifiable indication of the optimal stacking height and irrigation rate from the geo-mechanical point of view (or operating regimes that should be avoided).

- Extractive metallurgical

Rolling bottle leach tests are typically performed to first narrow the feasible ranges for the main leach parameters, followed by column leach experiments. Only the latter yield estimates of the reagent consumption and kinetic information that can be applied to heap leach process design. Column leach experiments in closed circuit with a metal recovery step can simulate the anticipated accumulation of chemical species in solution, and such solution samples can be used for detailed downstream purification and metals recovery testwork.

- Environmental

At least one column test should be dedicated to be continued for another couple of months after the completion of leaching, to study the chemical composition of the drainage solutions emanating from it over time, for the purpose of the environmental impact study.

- Microbiological

Molecular techniques, such as quantitative PCR, which will allow the identification and quantification of microbes in heap bioleach processes, are being developed at Mintek. It is envisaged that the ability to correlate microbial types and numbers to changes in the chemical and physical profile with time in the heap, would assist in solving process issues such as how a heap should be inoculated, which microbial cultures to add and when to inoculate.

An indication ought to be obtained of the effectiveness of different possible inoculation procedures, with respect to bacterial survival rate and lag time required to achieve a measurable oxygen uptake rate.

- Flowsheeting and optimisation

It has been illustrated how testwork towards the counter-current acid heap leaching of nickel laterite ores was applied to arrive at a conceptual flowsheet and optimisation of the acid balance.

Acknowledgements

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- 10 years in the Hydrometallurgy Division of Mintek, doing laboratory and pilot plant investigations on gold extraction by conventional cyanidation, heap leaching and in-stope leaching. Also developed and commercialised novel equipment for activated carbon regeneration during that time

- The past 13 years in the Biotechnology Division of Mintek, leading laboratory and pilot plant campaigns on the bioleaching of base metals, including the development of processes for the bioleaching of dirty chalcopyrite concentrates, the indirect bioleaching of zinc concentrates, the high temperature heap bioleaching of copper ore, and heap leaching administration software.

- Headed heap leaching and heap bioleaching amenability studies on mostly uranium and copper ores for a number of commercial clients. Current research topics include the geochemical interactions occurring between gangue and acid over the heap leach life cycle of an ore, and the benefits of bacterial activity to the heap bioleaching of uranium ore.

- Appointed as Manager of the Biotechnology Division in May 2009