

Performance evaluation of a carbon-in-pulp plant by dynamic simulation

by J.H. Schubert*, I.J. Barker*, and C.L.E. Swartz†

SYNOPSIS

A dynamic simulator of the leaching and adsorption cascades of a gold plant was developed and used to compare the effect of various disturbances on the overall efficiency of the plant. These comparisons show which disturbances most critically need to be controlled to optimize plant performance.

The simulator was based on an existing gold plant. Dynamic and steady-state data were collected on the plant and were used in the modelling of the process. Simple dual-rate models are used to describe the leaching and adsorption processes. Mole-balances of various species take into account the changes of concentrations in the leach, and also the movement of pulp and carbon up and down the adsorption cascade.

Fluctuations in the flowrate, density, and cyanide concentration of the feed to the leach have a negative effect on the efficiency of the leach, while carbon attrition was found to be an important factor in decreasing the efficiency of the carbon-in-pulp (CIP) section. Badly regulated transfers contribute towards the decreased efficiency of the CIP section, but overflows and carbon leakage have only a limited long-term effect. Various carbon profiles and transfer schemes were studied, and the results indicated that a slightly heavier loading at the bottom of the cascade is beneficial, while the type of transfer is relatively unimportant.

SAMEVATTING

'n Dinamiese simulator van die uitloog- en adsorpsiekaskades van 'n goudaanleg is ontwikkel en gebruik om die invloed van verskeie steurnisse op die algehele doeltreffendheid van die aanleg te vergelyk. Hierdie vergelyking toon die mees kritieke steurnisse wat beheer moet word om die aanleg se prestasie te optimaliseer.

Die simuleerder is op 'n bestaande goudaanleg gebaseer. Dinamiese en statiese data is op die aanleg versamel en gebruik in die modellering van die proses. Eenvoudige duale-tempo modelle word gebruik om die uitloog- en adsorpsieprosesse te beskryf. Molbalanse van verskeie spesies neem die verandering van konsentrasie in die loog, sowel as die beweging van pulp en koolstof op en af in die adsorpsiekaskade, in ag.

Fluktuasies in die vloei tempo, digtheid en sianiedkonsentrasie van die toevoer na die loog het 'n negatiewe invloed op die doeltreffendheid van die loog. Koolstofafsluyting blyk 'n verdere belangrike faktor in die afname in die doeltreffendheid van die koolstof-in-pulp (KIP) seksie te wees. Swak geregleerde oordragings dra by tot die verminderde doeltreffendheid van die KIP-seksie, maar oorloope en koolstoflekasie het slegs 'n beperkte langtermyn invloed. Verskeie koolstofprofile en oordragemas is bestudeer. Die resultate toon dat 'n ietwat swaarder lading aan die onderpunt van die kaskade voordelig is, terwyl die tipe oordrag relatief onbelangrik is.

INTRODUCTION

Research into gold-extraction processes tends to follow the price of gold: when the gold price was high in the early 1980s, research activity increased dramatically but, in the early 1990s, the low gold price dampened interest in new research. Yet, during precisely such difficult times, it is important to ensure that existing operations run efficiently. Some improvement is usually possible by more productive use of the available instrumentation and control hardware. Some additional simple—and cheap—controls may significantly improve production.

To provide the information needed in deciding what variables should be controlled, a dynamic simulator of the leaching and adsorption cascades of a gold plant was developed¹, based on information collected on a South African industrial plant. The simulation consists of a set of differential mole-balances, which are integrated simultaneously by a numerical integration routine.

* Measurement and Control Division, Mintek, Private Bag X3015, Randburg, 2125 Transvaal.

† Department of Chemical Engineering, University of Cape Town, Private Bag, Rondebosch, 7700 Cape Province.

© The South African Institute of Mining and Metallurgy, 1993. SA ISSN 0038-223X/3.00 + 0.00. Paper submitted April 1993; revised paper received July 1993.

The model was kept as simple as possible to limit the number of tuning constants needed. In control studies it is more important to ensure that the overall trends are correct and meaningful, rather than to choose a detailed model that will predict processes correctly at the microscopic level. For instance, the rates of leaching and adsorption can be most accurately described by complex distributed-rate models. The approach adopted was to use simple dual systems instead. Metallic gold in the ore is assumed to occur in two classes: largely liberated particles that leach quickly, and occluded or passivated particles that leach more slowly. Similarly, the sites at which the aurocyanide complex is adsorbed occur in two types of pores: the easily available sites are situated in fast-loading pores, while the other sites are located in slow-loading pores. The plant data were used to guide the choice of kinetic constants needed by this simple model.

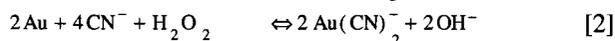
THE PLANT

Figure 1 shows the set-up of the simulated plant. The leach cascade consists of ten large agitated and well-aerated pachucas. The levels in adjacent pachucas interact, so that the flows between adjacent tanks depend on the levels in both tanks. The adsorption cascade consists of eight adsorp-

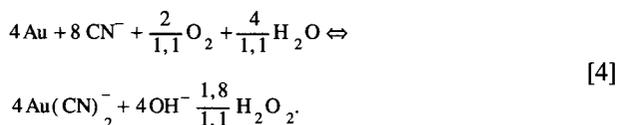
tion contactors physically arranged at successively lower levels, allowing the pulp to flow down the cascade by gravity. Horizontal screens prevent carbon from moving downstream, and carbon-containing pulp is periodically pumped upstream.

THE LEACHING MODEL

It has been known for decades that both cyanide and oxygen are required to leach gold. This is reflected in Bodländer's two reactions, [1] and [2], which sum to Elsner's equation [3]:



Finkelstein² reported that most gold dissolves by Bodländer's first equation [1], and only about 10 per cent of the peroxide produced is consumed in the second reaction [2]. A less elegant but more accurate equation than Elsner's is thus achieved by the addition of 0,1 times equation [2] to equation [1]. Balancing the equation and multiplying by $\frac{2}{1,1}$ result in equation [4], which resembles Elsner's equation:



The relative concentrations of oxygen and cyanide in the pulp affect the rate of leaching, as the reaction rate will be limited by the diffusion of the rarer reactant to the particle surface. A changeover from rate control by cyanide to rate control by oxygen has been reported^{3,4,5} to occur at a $[\text{CN}^-]:[\text{O}_2]$ of 4 to 10. Habashi's equation⁶, postulated in 1966, was considered

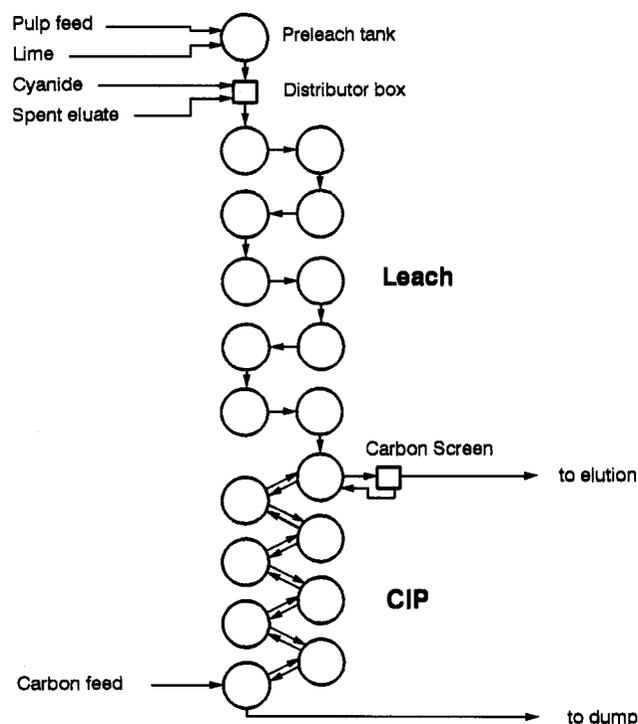


Figure 1—Plant sections included in the simulation

most suitable, as the form of this equation automatically takes the rate control changeover into account (this is more clearly visible in the modified equation [6] below):

$$\frac{dn_{\text{Au}}}{dt} = -\frac{2A_{\text{Au}} D_{\text{CN}^-} D_{\text{O}_2} C_{\text{CN}^-} C_{\text{O}_2}}{\delta (D_{\text{CN}^-} C_{\text{CN}^-} + \chi D_{\text{O}_2} C_{\text{O}_2})} \quad [5]$$

where n_{Au} is the number of moles of gold present (kmol),
 A_{Au} is the surface area of exposed gold (m^2),
 D_{CN^-} is the diffusivity of free cyanide in water at 25°C ($\text{m}^2\cdot\text{s}^{-1}$),
 D_{O_2} is the diffusivity of oxygen in water at 25°C ($\text{m}^2\cdot\text{s}^{-1}$),
 C_{CN^-} is the concentration of free cyanide in the pulp ($\text{kmol}\cdot\text{m}^{-3}$),
 C_{O_2} is the concentration of dissolved oxygen in the pulp ($\text{kmol}\cdot\text{m}^{-3}$),
 δ is the thickness of the boundary layer (m), and
 χ is the ratio of stoichiometric constants of CN^- to oxygen, i.e. 4,4 in equation [4] (dimensionless).

This equation was modified by the introduction of an occlusion factor, s , which reduces the rate of leaching from Habashi's ideal case to a more realistically slow rate. The equation was then simplified as shown below:

$$\frac{dn_{\text{Au}}}{dt} = -\frac{6s\mu_{\text{Au}} D_{\text{O}_2}}{\rho_{\text{Au}} \bar{R}_{\text{Au}} \delta} n_{\text{Au}} \left[\frac{1}{C_{\text{O}_2}} + \frac{1,5\chi}{C_{\text{CN}^-}} \right]^{-1} = -k_{\text{Au}} n_{\text{Au}} \left[\frac{1}{C_{\text{O}_2}} + \frac{1,5\chi}{C_{\text{CN}^-}} \right]^{-1} \quad [6]$$

where s is the occlusion factor (dimensionless),
 μ_{Au} is the molecular mass of gold ($\text{kg}\cdot\text{kmol}^{-1}$),
 ρ_{Au} is the density of gold ($\text{kg}\cdot\text{m}^{-3}$),
 \bar{R}_{Au} is the average radius of gold particles in the ore (m), and
 1,5 is the ratio of D_{CN^-} to D_{O_2} .

The rate constants used for the fast- and the slow-leaching gold respectively are

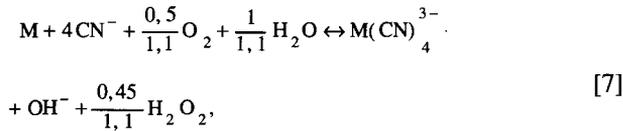
$$k_{\text{Au, fast}} = 1,215 \times 10^3 \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}, \text{ and}$$

$$k_{\text{Au, slow}} = 8,501 \times 10^1 \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}.$$

Equation [6] therefore includes terms for all the relevant species: gold, cyanide, and oxygen. The factor $1,5\chi = 6,6$ implies that oxygen becomes rate-controlling when its concentration becomes less than $\frac{1}{6,6}$ that of cyanide, which agrees with the experimental results reported above.

The characteristics of gold in the feed vary considerably. The gold particles occur in various sizes and shapes. Some may be liberated, while others are occluded to varying degrees. Some particles may also be passivated by being in contact with conducting minerals⁷. Instead of the use of a detailed and cumbersome distribution description, gold particles are modelled as belonging to just two discrete classes, a slow-leaching and a fast-leaching class. Most of the gold is found to be fast-leaching, with only about 7 per cent being slow-leaching.

Both cyanide and oxygen are consumed in various side reactions. For instance, other metals such as silver, copper, nickel, and iron will also be leached in the presence of cyanide and oxygen. The effect of all these metals is accounted for by the inclusion of a single competing metal, M, which is also assumed to occur in slow-leaching and fast-leaching varieties:



with the rate equation

$$\frac{dn_M}{dt} = - \frac{6s\mu_M D_{O_2}}{\rho_M \bar{R}_M \delta} n_M \left[\frac{1}{C_{O_2}} + \frac{1,5\chi}{C_{CN^-}} \right]^{-1} = - k_M n_M \left[\frac{1}{C_{O_2}} + \frac{1,5\chi}{C_{CN^-}} \right]^{-1}, \quad [8]$$

where n_M is the number of moles of the competing metal present (kmol),
 μ_M is the molecular mass of the 'metal' (kg·kmol⁻¹),
 ρ_M is the density of the 'metal' (kg·m⁻³), and
 \bar{R}_M is the average radius of 'metal' particles in the ore (m).

Both μ_M and ρ_M are the weighted average properties of the competing metals in the ore.

The rate constants used for the fast- and slow-leaching reactions of M respectively are

$$k_{M,fast} = 2,036 \times 10^3 \text{ m}^3 \cdot \text{kmol}^{-1} \cdot \text{s}^{-1}, \text{ and} \\ k_{M,slow} = 1,169 \times 10^1 \text{ m}^3 \cdot \text{kmol}^{-1} \cdot \text{s}^{-1}.$$

The leaching reaction of M is included for two reasons: first of all, the concentrations of the combined metals can be analysed fairly easily, so that their effect is quantifiable, but separate treatment of each would have been too cumbersome. Secondly, the inclusion of a 'metal'-cyanide species was desirable for the realistic simulation of the adsorption process.

It should be noted that the data collected on the plant were not suitable for rigorous curve fitting and the determination of exact rate constants. Instead, the relative sizes of the various rate constants were chosen in such a way that the overall effect resembled that of the true plant.

While the grade of gold in the ore is very much lower than the combined concentrations of all the other metals, the liquid concentration of the aurocyanide complex is a tenth of the 'metal'-cyanide concentration. It is therefore feasible to include only the leachable portion of 'metal', and to calculate a rate of leaching for this available 'metal' that resembles the measured one. However, the relative rate at which gold dissolves is initially very fast, and then slows down significantly, while the 'metal' seems to dissolve at a more even rate. The fast-leaching component of the gold is therefore large (93 per cent), and has a rate constant far greater than the slow-leaching fraction, while the two constants for the 'metal' are of similar magnitude.

Other side reactions include the oxidation of cyanide to cyanate, which Adams⁸ indicated to be the most likely reaction in a normal leach pulp:



with a simple rate equation:

$$\frac{dC_{CNO^-}}{dt} = k_{CNO^-} C_{CN^-} \frac{C_{O_2}}{C_{O_2}^{eq}}, \quad [10]$$

where $C_{O_2}^{eq} = 3,31 \times 10^{-7} \text{ kmol} \cdot \text{m}^{-3}$ is the equilibrium concentration of dissolved oxygen in the pulp, and

$k_{CNO^-} = 1,58 \times 10^{-6} \text{ s}^{-1}$, which was interpolated from the constants given by Adams⁸ for various cases.

The equilibrium concentrations of dissolved oxygen measured in the leach pachucas on the plant were found to be significantly higher than would have been expected at 1800 m above sea level. This is a result of the good mixing characteristics in the leach pachucas. Air introduced into the pulp is carried right down to the bottom of the pachucas, where the oxygen dissolves at high pressures.

The dissolution of oxygen in the pulp was, therefore, also included:



with the rate equation

$$\frac{dC_{O_2}}{dt} = k_{O_2} \left(C_{O_2}^{eq} - C_{O_2} \right), \quad [12]$$

where $k_{O_2} = 7,621 \times 10^{-5} \text{ s}^{-1}$.

THE ADSORPTION MODEL

Excellent research in the past few years^{9,10} has provided details of the mechanism of adsorption of gold cyanide onto carbon. Activated carbon is the carbon backbone remaining after the treatment of organic material at high temperatures. During the treatment, a large number of pores of varying size are burnt into the carbon. For convenience they are usually divided into macro-, meso-, and micropores, with the micropores accounting for by far the greater part of the available surface area. The number of adsorption sites in micropores is therefore higher, but an adsorbent particle takes longer to reach these sites because of longer diffusion times. Carbon was therefore modelled as consisting of two separate phases:

- a fast-loading phase (containing only macropores), and
- a slow-loading phase (containing only micropores)

where there is a larger component of the slow-loading phase. The gold that has been adsorbed at the sites in each of these different phases is accounted for separately. The division into these phases simulates the initial fast loading followed by a long period of very slow loading, which has often been reported.

The rate equation chosen is the linear adsorption/desorption equation first proposed by Nicol *et al.*¹¹:

$$\frac{dq_{\text{Au(CN)}_2^-}^-}{dt} = k_{\text{Au(CN)}_2^-} \left(C_{\text{Au(CN)}_2^-} - K_{\text{Au(CN)}_2^-} q_{\text{Au(CN)}_2^-} \right) n_{C,j} \quad [13]$$

where $q_{\text{Au(CN)}_2^-}$ is the loading of Au(CN)_2^- on carbon phase j ($\text{mol}\cdot\text{mol}^{-1}$ of carbon $^{-1}$),

$C_{\text{Au(CN)}_2^-}$ is the concentration of Au(CN)_2^- in the pulp ($\text{kmol}\cdot\text{m}^{-3}$), and

$n_{C,j}$ is the amount of carbon of phase j in the tank (kmol).

The rate constant used for the two phases of coarse carbon are

$$K_{\text{Au(CN)}_2^-}^{\text{fast}} = 4,4 \times 10^{-4} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}, \text{ and}$$

$$K_{\text{Au(CN)}_2^-}^{\text{slow}} = 2,2 \times 10^{-4} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}.$$

The linear equilibrium constants for the two phases are

$$K_{\text{Au(CN)}_2^-}^{\text{fast}} = 0,1 \times 6,5 \times 10^{-6} \text{ kmol}\cdot\text{m}^{-3}, \text{ and}$$

$$K_{\text{Au(CN)}_2^-}^{\text{slow}} = 0,9 \times 6,5 \times 10^{-6} \text{ kmol}\cdot\text{m}^{-3}.$$

Even though the linear isotherm is reported¹² to be less accurate at very low and very high loadings, it was chosen because it is simple and has only two constants, which can be determined easily. Furthermore, during normal operation on a plant, extreme loadings of gold are rare.

The attrition of carbon is one of the main disturbances in a CIP plant. This factor was therefore included in the simulation, the rate of attrition being chosen as proportional to the concentration of carbon in the pulp, as suggested by Whyte *et al.*¹³. If this is written in terms of moles,

$$\frac{dn_{C\text{-fines}}}{dt} = k_{\text{abrasion}} n_{C\text{-granules}} \quad [14]$$

where $n_{C\text{-fines}}$ = the number of moles of carbon fines (kmol),

$n_{C\text{-granules}}$ = the number of moles of coarse carbon granules in the tank (kmol), and

$k_{\text{abrasion}} = 2,3 \cdot 10^{-8} \text{ s}^{-1}$
 $\equiv 0,083 \text{ g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ as suggested by Whyte *et al.*¹³. (The carbon concentration on the plant was maintained at $25 \text{ kg}\cdot\text{m}^{-3}$, which is within the range for which this rate constant was suggested.)

The small abraded pieces of carbon will also adsorb gold, and therefore a third carbon phase with a large number of available sites was included. The rate of loading onto these sites (as well as the rate of desorption from these pores) is high because of the small size of the particles. The form of the rate equation is the same as in equation [13], with

$$k_{\text{Au(CN)}_2^-}^{\text{fine}} = 4,4 \times 10^{-4} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}, \text{ and}$$

$$K_{\text{Au(CN)}_2^-}^{\text{fine}} = 6,5 \times 10^{-6} \text{ kmol}\cdot\text{m}^{-3}.$$

Adsorption of other species, such as the metal-cyanide complex and free cyanide, was also included. The adsorption equation has the same form as equation [13]. The rate and equilibrium constants are listed above. Unfortunately, because of the lack of suitable data, the effects of competitive loading (such as displacement of species by others at high loadings) and pH-dependence (preferential loading depending on pH) were not included.

For the metal-cyanide:

$$k_{\text{M(CN)}_4}^{\text{fast}} = 9,0 \times 10^{-5} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}$$

$$K_{\text{M(CN)}_4}^{\text{fast}} = 0,1 \times 1,2 \times 10^{-3} \text{ kmol}\cdot\text{m}^{-3}$$

$$k_{\text{M(CN)}_4}^{\text{slow}} = 4,5 \times 10^{-5} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}$$

$$K_{\text{M(CN)}_4}^{\text{slow}} = 0,9 \times 1,2 \times 10^{-3} \text{ kmol}\cdot\text{m}^{-3}$$

$$k_{\text{M(CN)}_4}^{\text{fine}} = 9,0 \times 10^{-5} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}$$

$$K_{\text{M(CN)}_4}^{\text{fine}} = 1,2 \times 10^{-3} \text{ kmol}\cdot\text{m}^{-3}.$$

For cyanide:

$$k_{\text{CN}^-}^{\text{fast}} = 2,0 \times 10^{-5} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}$$

$$K_{\text{CN}^-}^{\text{fast}} = 0,1 \times 1,5 \times 10^{-3} \text{ kmol}\cdot\text{m}^{-3}$$

$$k_{\text{CN}^-}^{\text{slow}} = 1,0 \times 10^{-5} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}$$

$$K_{\text{CN}^-}^{\text{slow}} = 0,9 \times 1,5 \times 10^{-3} \text{ kmol}\cdot\text{m}^{-3}$$

$$k_{\text{CN}^-}^{\text{fine}} = 2,0 \times 10^{-5} \text{ m}^3\cdot\text{kmol}^{-1}\cdot\text{s}^{-1}$$

$$K_{\text{CN}^-}^{\text{fine}} = 1,5 \times 10^{-3} \text{ kmol}\cdot\text{m}^{-3}.$$

THE HYDRODYNAMICS

The leaching pachuca and the CIP vessels were modelled as continuous stirred-tank reactors. The flow out of each pachuca depends on the level in that and in the following pachuca. The flow from each CIP tank depends on the level in only that particular tank. The CIP vessels contain horizontal screens, which allow the pulp and carbon fines to pass downstream unhindered, but retain the coarse carbon. The coarse carbon can move downstream only if a screen overflows or tears.

On the plant, and thus also in the simulator, a carbon-pulp mixture is pumped from each tank to the one above during carbon transfers. In practice, the carbon-transfer pumps are switched on at relatively regular intervals, and are switched off when enough carbon has been transferred. In the simulation, the transfer pumps could be switched on and off as desired, so that various transfer schemes could be investigated. These included changing the frequency of transfers, and at the same time changing the magnitude of transfers to keep the amount of carbon transferred constant in the long term; changing the timing of transfers, etc.

All the component variables are expressed in terms of moles. Concentrations are then simply average concentrations over the whole tank. The amount of material in each tank is calculated by taking into account the following general differential mole-balance:

$$\frac{dn_{i,j}}{dt} = \dot{n}_{i-1,j} - \dot{n}_{i,j} + \sum_{m=1}^M \alpha_{j,m} r_m(n_{i,1}, n_{i,2}, \dots, n_{i,N}), \quad [15]$$

for $i = 1 \dots NT$; $j = 1 \dots N$

where $\dot{n}_{i,j}$ is the number of moles of component j flowing out of tank i ($\text{kmol}\cdot\text{s}^{-1}$),

$\alpha_{j,m}$ is the stoichiometric constant of component j in reaction m ,

r_m is the rate of reaction m , which is potentially a function of all n in tank i ($\text{kmol}\cdot\text{s}^{-1}$),

M is the total number of reactions,

N is the total number of components, and

NT is the total number of tanks in the system.

THE SIMULATOR

A stream-based approach is applied to the simulator to ensure its flexibility in terms of plant configuration. Process units are initially defined (not necessarily in any specific order), and then the streams are defined to run between the different processes. The necessary data on the plant configuration, the chemistry, and the physical properties of the constituents are read in from data files.

The program initially allows the specific scenario for the next simulation to be set. This gives the user the option of altering the transfer schedule, choosing the size and timing of transfers, and choosing whether attrition or carbon leakage should be included in the simulation run, etc. The user also has the option of using dynamic plant data in the feed streams.

The numerical integration is performed by a variable-step Bulirsch-Stoer integration routine¹⁴. The variables are divided into two groups: algebraic and state variables, where state variables are integrable, while algebraic variables are derived variables. The integration proceeds at the same speed for all state variables, i.e. a chunked or simultaneous approach is used.

RESULTS AND DISCUSSION

In the interpretation of the results, it must be borne in mind that the efficiencies reported below are not true efficiencies. The results should rather be seen as numbers relative to a 'base case' of a largely undisturbed, ideal system. Conclusions may be drawn only by comparing the results with one another, and thereby determining which effects are most detrimental to the efficiency of the plant.

Leaching Section

From tests carried out on the industrial plant, it was observed that the leaching efficiencies were generally very high (more than 95 per cent). The kinetic constants of the chemical reactions were therefore chosen in such a way as to give the 'base case' a leaching efficiency of 99,59 per cent, where the efficiency is calculated by taking only the exposed (i.e. soluble) gold into account. The 'base case' simulation was the ideal case, in which the feed flowrate remained constant, the cyanide addition was constant, and sufficient dissolved air was available in the pulp.

The pulp entering the leaching plant already contains a fair amount of dissolved oxygen, which dissolves during the thickening process, and also in an air-agitated surge tank. A simulation was run to investigate the effect of no dissolved oxygen in the feed. The efficiency decreased to 99,55 per cent, which is a negligible decrease. The agitation of the pachucas and the method of aeration are therefore sufficient to ensure adequate dissolved oxygen levels.

Although the dissolved oxygen levels on the plant were satisfactory, the cyanide concentration fluctuated widely. Cyanide concentrations are not measured continuously on the plant, but are measured by manual titrations once or twice a shift. In between, the operator is forced to adjust the addition of cyanide by intuition and experience. In an effort to ensure that enough cyanide will always be available, it is added in great excess. Unfortunately, the feed flowrate tends to fluctuate considerably, and the cyanide concentration is often far from the desirable level. Another major disturbance to the

cyanide control is due to the returning of spent eluate to the leach. This eluate stream is extremely alkaline and contains a great deal of cyanide, but is not adequately taken into consideration by the plant control scheme.

In an attempt to quantify the effect of these disturbances on the leaching efficiency, this case was simulated by the reading of continuous data previously recorded on the plant (such as feed pulp flowrate, feed density, and cyanide addition rate) into the simulator. The resulting concentrations of cyanide in tanks 1 and 10 are shown in Figure 2. Unfortunately, the actual spot measurements of cyanide taken on the plant are not available. The leaching efficiency for this simulated case was reduced to 99,24 per cent.

It therefore seems worth while to direct some attention at improving cyanide addition control. At present, large excesses of cyanide are maintained to prevent gold from being lost. Most of this cyanide is simply wasted, as it is pumped out to the dump and, apart from the wastage, could present an increased environmental hazard. A simple proportional controller linked to the flowrate of the feed pulp would ensure the correct addition levels to maintain the cyanide concentration at reasonable limits, so that all the gold can dissolve and the wastage of cyanide is reduced. Additions of spent eluate can easily be allowed for if the dosage of cyanide is adjusted while spent eluate is being added.

Adsorption Section

Any CIP cascade using intermittent transfers will, by definition, never reach a steady state. Carbon is transferred frequently to prevent equilibrium between the solution and the carbon phases, thus maintaining a fast rate of loading. During transfers, both pulp and carbon are moved up the cascade, upsetting the process in the short term by back-mixing of the pulp. But in the long term the countercurrent method of contacting pulp and carbon ensures high efficiencies.

Figure 3 shows the loading of carbon in a tank over a two-week period. Initially, the plant is assumed to be totally empty, and the leach cascade and CIP cascade are filled by a perfectly constant feed stream within about 2,5 days. Transfers are idealized, in that exactly 5000 kg of carbon are transferred every 16 hours (i.e. every second shift), and each transfer takes about 3 hours. The transfers take place simultaneously. The curves show that a pseudo-steady state

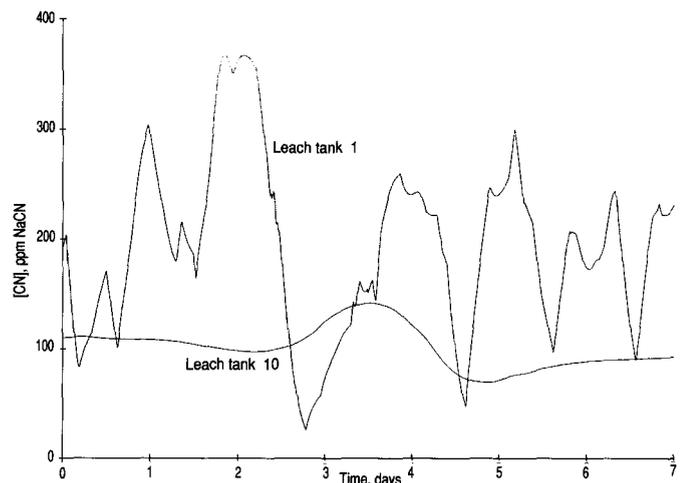


Figure 2—Simulated variations in cyanide concentration using dynamic plant data

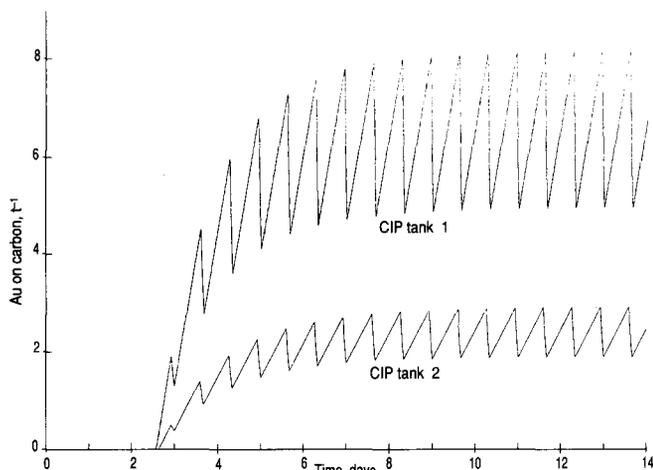


Figure 3—Simulated variations in gold loading on carbon

is reached by the beginning of the second week, in which successive peaks are identical.

An estimate of the efficiency of adsorption can be made from a comparison of the amount of gold adsorbed over a period to the total amount that entered the system. The case described, which is the 'base case' for the adsorption section, has a calculated efficiency of 97,99 per cent, compared with measured efficiencies on the plant of between 97 and 99,5 per cent.

For comparison, another simulation was done, in which the transfers were smaller (2500 kg) and more frequent (every 8 hours). In this case, each transfer took less time, but over a two-day period the same amount of carbon was transferred as in the base case; however, the efficiency was slightly higher, at 98,08 per cent, as shown in Table I.

Table I also shows the efficiency of two other simulated cases:

- consecutive transfers: initially, carbon is removed from the very first tank, and only when enough has been removed will carbon be transferred from the second to the first tank, etc. (again, this was done at the two transfer rates as shown)
- continuous transfers: the transfer pumps are kept running continuously, transferring the same amount of carbon within a two-week period as during the intermittent transfer schemes.

Smaller, more frequent transfers are more efficient. Consecutive transfers disturb the system for a longer period than the other transfers (especially when 5000 kg of the available 5700 kg are to be removed from a tank), and therefore lead to lower performance than the simultaneous transfers. Continuous transfers seem most efficient, but may be impracticable on a real plant.

Table I
Transfer schemes

Transfer scheme	Relative efficiency, %
Simultaneous 5000 kg/16 h	97,99
	2500 kg/8 h
Consecutive 5000 kg/16 h	97,66
	2500 kg/8 h
Continuous 5000 kg/16 h	98,08

In contrast to the ideal situation, normal plant transfers are irregularly spaced, and significantly different amounts of carbon are transferred. The flowrates of the transfer streams were measured on the industrial plant, and the transfer periods were recorded. When these data were included in a simulation run, the efficiency dropped to 96,15 per cent, and the carbon profile along the cascade was upset badly, as can be seen in Figure 4. The amount of carbon that should be present in each tank at any one time according to design specification is about 5700 kg, or 2 per cent by volume. In the simulated plant, one tank contained about four times this amount, while another contained almost no carbon.

The effect of distorted carbon profiles was tested by loading either the first or the last tank in the cascade with 1,5 times the normal amount of carbon (giving top-heavy and bottom-heavy profiles respectively). The total amount of carbon in the cascade was kept constant. The results, as shown in Table II, indicate that the heavier loading of the last tank was most efficient.

An upset carbon profile also upsets the solution profile, causing a loss of efficiency. In addition to the deliberately distorted profiles mentioned above, other disturbances to the carbon profile were also investigated, including attrition, carbon leaking through the screen, and screen blockages followed by overflows.

Overflows and carbon leakage generally have only a local effect on the carbon profile, and their long-term effects on the overall efficiency are negligible. In contrast, the effect of attrition and the movement of carbon fines down the cascade was quite remarkable. An attrition rate of 83 g/t per hour would mean that about 3,7 kg of carbon are lost per hour, and yet this reduced the efficiency, as calculated by the simulator, by 2 per cent. If the base case had thus been

Table II
Effect of carbon profiles

Profile	Relative efficiency, %
Top-heavy	97,73
Flat	97,99
Bottom-heavy	98,11

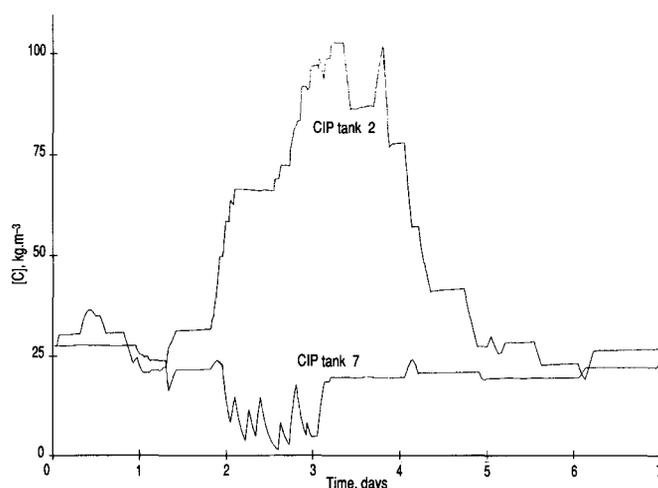


Figure 4—Simulated variations in carbon concentrations caused by different flowrates

simulated without carbon abrasion, its efficiency would have been very nearly 100 per cent.

The reason for the great effect of carbon attrition lies in the fast adsorption of gold onto, and desorption from, the carbon fines—the small carbon particles adsorb gold quickly from a concentrated solution. A significant amount is adsorbed, and causes a noticeable drop in the solution concentration at the head of the cascade. As the carbon fines are washed downstream and come into contact with a less concentrated solution, gold begins to be desorbed. This, in turn, causes the concentrations of gold in solution in the lower tanks to rise. The overall effect of carbon attrition is to smooth out the solution profile in the cascade, thus reducing the efficiency of the plant.

From the foregoing discussion, it becomes clear that the carbon profile along the CIP cascade must be controlled carefully. This is achieved by preventing carbon from moving downstream (by leaking through torn screens or by overflowing blocked screens), and also by ensuring that the correct amounts of carbon are moved up the cascade by regulating the timing and duration of transfers. The accurate on-line monitoring of carbon concentration in CIP tanks is possible today, and should be considered.

CONCLUSIONS

The dynamic simulator, which was developed using a relatively simple model for both the adsorption and leaching sections, produced results that indicated that certain disturbances needed to be controlled. Some idealized simulations were used to compare various aspects of both the leaching and adsorption processes; but, more usefully, dynamic plant data were used by the simulator to recreate certain situations that had occurred on the plant, pointing to improvements that can be incorporated in the present control strategy.

For instance, the control of cyanide addition could be improved substantially by an inexpensive ratio-control system that uses the flowrate of feed pulp to the leach as an input signal. This is particularly true for the plant under consideration, as the feed flowrate is already being monitored. Tighter control on the amount of cyanide added not only prevents wastage due to excessively high concentrations, but also prevents gold loss during periods of high pulp flowrates.

The cause of the main disturbance in the CIP cascade is unfortunately not controllable. Attrition is a process that will automatically occur wherever activated carbon is exposed to a rough, abrasive environment. As long as attrition is considered and accounted for at the design stage, its effect is acceptable and can be allowed for.

In contrast, the transfer of carbon in the cascade is very much a controllable input. Carbon concentrations should be maintained close to design specifications by monitoring of the amounts in the tanks, the regular starting of transfers, and careful planning and controlling of transfer durations.

While the efficiencies of both the leaching and adsorption sections are already high, the high value of the product makes even slight improvements in efficiency financially rewarding, especially since these can be achieved at little or no extra cost.

ACKNOWLEDGEMENTS

This paper is published by permission of Mintek. Appreciation is expressed for the cooperation of the plant management, who allowed data from the plant to be used in this investigation.

REFERENCES

1. SCHUBERT, J.H. Dynamic simulation of the leaching and adsorption sections of a gold plant. M.Sc. thesis, University of Cape Town, April 1992.
2. FINKELSTEIN, N.P. The chemistry of the extraction of gold from its ores. *Gold metallurgy in South Africa*. R.J. Adamson (ed.). Johannesburg, Chamber of Mines of South Africa, 1972. Chapter 10. pp. 284–351.
3. DEITZ, G.A., and HALPERN, J. Reaction of silver with aqueous solutions of cyanide and oxygen. *J. Met., Trans. AIME*, 1953. pp. 1109–1116.
4. KUDRYK, V., and KELLOGG, H.H. Mechanism and rate-controlling factors in the dissolution of gold in cyanide solution. *J. Met., Trans. AIME*, vol. 6, no. 5. 1954. pp. 541–548.
5. KAKOVSKII, I.A., and KHOLMANSKIKH, N.B. A study of the kinetics of the cyaniding process for copper and gold. *Izvest. Akad. Nauk SSR. Otdel. Tekh Nauk, Met. i Toplivo*, no. 5. 1960. pp. 207–218. (In Russian).
6. HABASHI, F. The theory of cyanidation. *Trans. Min. Soc. AIME*, no. 235. 1966. pp. C219–C225.
7. LORENZEN, L., and VAN DEVENTER, J.S.J. Electrochemical interactions between gold and its associated minerals during cyanidation. *Hydrometallurgy*, vol. 30. 1992. pp. 177–194.
8. ADAMS, M.D. The chemical behaviour of cyanide in the extraction of gold. 1. Kinetics of cyanide loss in the presence and absence of activated carbon. *J. S. Afr. Inst. Min. Metall.*, vol. 90, no. 3. 1990. pp. 37–44.
9. McDUGALL, G.J., ADAMS, M.D., and HANCOCK, R.D. Models for the adsorption of aurocyanide onto activated carbon. Part I. Solvent extraction of aurocyanide ion pairs by 1-pentanol. *Hydrometallurgy*, vol. 18. 1987. pp. 125–138.
10. JONES, W., KLAUBER, C., and LINGE, H.G. Fundamental aspects of gold cyanide adsorption on activated carbon. *Gold forum on technology and practices. World Gold '89, Reno, Nevada*. R.B. Bhappu and R.J. Harden (eds.). SME and AusIMM, 1989. pp. 278–281.
11. NICOL, M.J., FLEMING, C.A., and CROMBERG, G. The adsorption of gold cyanide onto activated carbon. Part I: The kinetics of adsorption from pulps. *J. S. Afr. Inst. Min. Metall.*, vol. 84, no. 2. 1984. pp. 50–54.
12. JOHNS, M.W. Model application. SAIMM Carbon School, Mintek, 1986. Lecture 5.
13. WHYTE, R.M., DEMPSEY, P., and STANGE, W. The development and testing of the AAC 'pump-cell' at Vaal Reefs Exploration and Mining Company Limited. *International Deep Mining Conference: Innovations in Metallurgical Plants*. Johannesburg, South African Institute of Mining and Metallurgy, 1990. SAIMM Symposium Series no. S10, vol. 1, pp. 169–180.
14. PRESS, W.H., FLANNERY, B.P., TEUCHOLSKY, S.A., and VETTERLING, W.T. *Numerical recipes: The art of scientific computing*. Cambridge, Cambridge University Press, 1986. pp. 547–577.