A dynamic CIP simulation using Matlab Simulink

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ABSTRACT

Carbon-in-pulp (CIP) and Carbon-in-leach (CIL) processes are used extensively in the gold mining sector to recover aurocyanide from solution. This paper discusses the modelling of these operations, using various simplifying assumptions, in order to simulate the effect of changing operating conditions on the dynamics of the system. It is assumed that the adsorption and leaching rates are a function of concentration difference between the source phase and recipient phase. The simulation was set up using Matlab's Simulink interface. Plant variables are solved using a medium scale Newtonian search algorithm in Matlab, where the differences between the actual and predicted plant outputs are minimized on a continuous time-line.

INTRODUCTION

The computational power available today enables the increasingly sophisticated analysis of process operations. However, there is a dark side – garbage in remains garbage out. Plant operators do not have the time or ambience to reflect deeply on their processes or to master the use of powerful yet complex modern software in order to analyze them. There is a need for relatively simple, robust models that fit operating data and enable plant operators to analyze and understand their processes better in order to make better operating decisions that benefit the bottom line. This paper presents an example of such a model.

Carbon in pulp (CIP) and carbon in leach (CIL) technology is deceptively simple. It will recover gold effectively as long it is operated correctly. When things go wrong, though, it loses or locks up gold. Retention times in these plants are relatively long and the process responds correspondingly slowly to changes to its controlled variables. This makes the intuitive diagnosis and correction of deviations difficult. Operators might wisely err on the side of caution, not recovering gold as cost efficiently as possible because the consequences of a mistake are much more expensive than a measure of process inefficiency such as a higher than necessary reagent addition. In today's world, though, the pressure to reduce costs is relentless. The only safe way to keep forcing costs down is *via* an appropriate understanding of the process. Modelling is arguably the best route to such understanding.

Various gold leaching and adsorption models have been proposed in the past [Schubert *et al* (1993), Habashi (1966)]. Most of these models are relatively complex and require the determination or estimation of parameters such as surface area, diffusivity, occlusion factors and particle radii. They are particularly difficult to apply when the person wielding the model does not have the time to fully master both the model and the software with which it is implemented. No matter how good the model itself may be, inappropriate use, whether because of time pressure, insufficient knowledge, inappropriate values for input parameters or any other cause, can easily lead to adverse consequences. Plant operators should fear being made to use complex models as part of their operating arsenal.

This study uses simple adsorption and leaching rate equations to predict the dynamic performance of CIP/CIL plants under varying operating conditions. The objective was to develop a robust tool to help plant operators achieve optimum efficiency, uncover sensitivities to specific operating parameters and ultimately achieve significantly greater control over the process. A major constraint imposed on this exercise was that the values of whatever parameters are required, such as values of the constants in the leaching and adsorption rate equations, residence times, etc., must be readily available on the plant concerned or fitted to plant operating data and not have to be determined separately, for example by means of laboratory experiments.

LEACHING MODEL

The chemical reaction between gold and cyanide involves oxygen and water as well as the gold and cyanide, i.e.

$$4Au + 8CN^- + O_2 + 2H_2O \Leftrightarrow 4Au(CN)_2^- + 4OH^- \qquad (1)$$
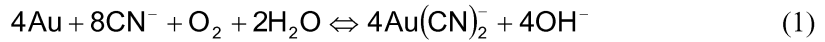
The amounts of solid gold, aurocyanide, dissolved cyanide and oxygen present determine the kinetics and equilibrium of the reversible gold dissolution reaction. For the purposes of this study, oxygen was assumed to be present in excess and not to control the rate of gold leaching. The pH of the system is controlled by the addition of lime, meaning that the concentration of hydroxide can be assumed to be steady and not control the rate of dissolution of gold. The reaction can therefore be thought of as a function of the levels of cyanide, dissolved gold and solid gold, as follows.

$$\text{Dissolution} = f[C_S, C_L, C_{CN^-}], \text{ assuming excess } O_2 \text{ and } OH^- \qquad (2)$$

For any given level of free cyanide and pH there will be a maximum solubility of aurocyanide. An increase in the concentration of free cyanide will increase the distance from equilibrium and *vice versa*. Similarly, an increase in aurocyanide concentration will decrease the distance from equilibrium and *vice versa*.

Assuming that the rate of the dissolution reaction is a linear function of the distance from equilibrium and also a linear function of the amount of undissolved gold remaining in the solids leads to the following rate equation.

$$\frac{dC_S}{dt} = k_L \left(K_L C_S - \frac{C_L}{C_{CN^-}} \right) \qquad (4)$$

where C_S is the gold concentration in the solids,
C_L is the gold concentration in the liquid,
C_{CN}^- is the cyanide concentration in the liquid,
k_L is a leaching rate constant and
K_L is a solubility constant.

Eq. 4 implies that the amount of undissolved gold present affects the maximum solubility of the aurocyanide complex, which is not theoretically correct. However, this equation is merely meant to represent the rate of dissolution of gold, rather than explain it. The purpose of this study was to examine the application of simple linear models of the chemistry to the dynamic simulation of an operating CIP/CIL plant. More rigorous models of the chemistry, while certainly more intellectually satisfying, would entail

significantly more computational complexity and defeat the purpose of this study. That approach is left to future work. This work used the admittedly highly simplified approximation of linearity to see where it would lead.

Many other elements in gold ores, including iron, copper, nickel and silver, compete with gold for the available cyanide and must also be accounted for in the cyanide balance. For simplicity these other metallic species were lumped together as the single metal M that is oxidized to the trivalent state and accounted for in the cyanide balance as follows.

$$2M + 6CN^- + O_2 + 2H_2O \Leftrightarrow M_2(CN)_6^{2-} + 4OH^- \qquad (5)$$
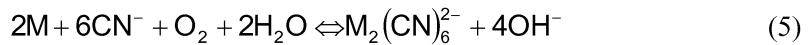
A similar lumping of metallic species in CIP/CIL operations has been proposed in the past (Shubert *et al*).

Leaching in the CIP/CIL plant is therefore represented by two reactions, each with its own kinetic and equilibrium parameters, competing for the available cyanide.

ADSORPTION MODEL

The adsorption model selected for this study is the one proposed by Nicol *et al* (1987). It was chosen because of its simplicity.

$$\frac{dC_L}{dt} = k_A\left(K_A C_L - C_C\right) \qquad (6)$$

where C_C is the concentration of gold on the carbon,
     k_A is a rate constant,
     K_A is an equilibrium constant
and the other symbols retain their meanings from above.

Again, four parameters are needed to predict the adsorption rates, namely rate and equilibrium parameters for gold and for the lumped metal species M.

MASS BALANCES

The material balance for a given species around any piece of process equipment, and also around entire processes, is given by the first law of thermodynamics, *viz.*

$$Accumulation \; = \; In - Out + Reaction$$

If the species concerned is formed by reaction, the *Reaction* term is positive, and if it is consumed by reaction that term is negative. Each stage in a CIP/CIL plant is a mixed reactor, so the composition of the mixture inside the stage is the same as that of its outflow. This leads to the following material balances for gold and a similar set for the lumped metal M, for each stage N in the train.

$$M_{L,N}\frac{dC_{L,N}}{dt} = L.C_{L,N-1} - L.C_{L,N} + k_L\left(K_L.C_{S,N} - \frac{C_{L,N}}{C_{CN^-,N}}\right).M_{S,N} - k_A\left(K_A.C_{L,N} - C_{C,N}\right)M_{L,N} \quad (8)$$

$$M_{S,N}\frac{dC_{S,N}}{dt} = S.C_{S,N-1} - S.C_{S,N} - k_L\left(K_L.C_{S,N} - \frac{C_{L,N}}{C_{CN^-,N}}\right).M_{S,N} \quad (9)$$

where L is the liquid flow rate through stage N,
$\quad\quad$ S is the solid flow rate through stage N,
$\quad\quad$ M_S is the mass of solids in stage N,
$\quad\quad$ M_L is the mass of solution in stage N
and the other symbols retain their meanings from before.

The process, as set up in the simulation, is unsteady with respect to carbon loading. Carbon transfer occurs periodically, when a fraction F_C of the carbon from stage $N+1$ is transferred to stage N. The interval between carbon transfers can range from zero to infinity (where 0 approximates steady carbon flow). A value of 45 minutes was used in this study. The initial carbon loading for stage N is re-calculated just after each carbon transfer, as follows.

$$C_{C,N,t=0} = C_{C,N,t=ti}.(1 - F_C) + C_{C,N+1,t=ti}.F_C \quad (10)$$

The carbon loading in stage N at time t after the carbon transfer is calculated by the following equation.

$$C_{C,N,t=t} = \frac{C_{C,N,t=0}.M_A + \int\limits_{t=0}^{t=t}k_A\left(K_A.C_{L,N} - C_{C,N,t=t}\right)M_L}{M_A} \quad (11)$$

where M_A is the mass of carbon in stage N and the other symbols are as before.

The calculated loading is substituted into Eq.8. This causes the adsorption rate, and hence the aurocyanide concentration, to vary with carbon loading. This, in turn, causes the rate of leaching to exhibit the same periodic behaviour.

The effects of back-mixing due to the carbon transfers must also be accounted for. The pulp concentrations of each tank are updated immediately after each carbon transfer, as follows.

For the liquid phase:

$$C_{L,N,t=0} = C_{L,N,t=ti}.(1 - F_C) + C_{L,N+1,t=ti}.F_C \qquad (12)$$

For the solid phase:

$$C_{S,N,t=0} = C_{S,N,t=ti}.(1 - F_C) + C_{S,N+1,t=ti}.F_C \qquad (13)$$

The equations for the other metal species are similar. The two sets of equations are linked by cyanide consumption.

SIMULATION

Many things affect the CIP/CIL process, for example carbon fouling, preg-robbing, carbon breakage, and others. However, these are not things over which the plant operators have direct control and they would be difficult to isolate from the overall rate and equilibrium parameters anyway. Factors such as these can be said to be implicitly incorporated in the values of the parameters in the model. The simulation makes use of the following simplifying assumptions.

- The pH is held at a level where it does not control the rate of leaching or adsorption.

- Carbon elution and regeneration are efficient and carbon fouling does not affect the rate of adsorption.

- Carbon breakage can be expressed as a fixed percentage of the amount of carbon transferred with the gold loading on carbon fines being equal to the gold loading in the final stage.

- Carbon transfers are effectively instantaneous.

The effect of back-mixing due to carbon transfers is accounted for in the simulation. The simulation was set up for six stages in series, but can be altered easily. The following inputs are required:

- Solids feed rate (t/s)
- Liquid feed rate (t/s)
- Carbon mass per stage (t)
- Mass solids per stage (t)
- Mass liquid per stage (t)
- Iinterval between carbon transfers (s)
- Fractional carbon transfer (fraction of carbon in stage $N+1$ transferred to N)
- Cyanide concentration in liquid feed (g/t)
- Concentration of gold in solid feed (g/t)
- Concentration of gold in liquid feed (g/t)
- Concentration of M in solid feed (g/t)
- Concentration of M in liquid feed (g/t)
- Elution efficiency for gold and M (fraction)
- Estimate of initial gold and M loading on carbon (g/t)
- Kinetic and equilibrium parameters for gold and M (K_X and k_X (s^{-1}))

The mass of solids and liquids per stage can be specified for individual stages to allow varying stage sizes. The simulation also allows the user to specify additional cyanide feed to any stage.

A medium scale Newtonian search algorithm minimizes the error between the outputs of a stage and the inputs to the following stage to ensure that mass is conserved in every stage as well as in the overall system. Each stage contains of two subsystems, one for gold and for M, which are linked through the cyanide consumption. Carbon loading and elution for gold and other metals are treated separately. Both subsystems take the same inputs, with the exception of concentrations and kinetic and equilibrium parameters. These two subsystems each contain four more subsystems, *viz.*

- The carbon loading subsystem regulates the periodic loading of carbon and calculates initial loading after every transfer.

- The adsorption subsystem contains the adsorption rate expression.

- The leaching subsystem contains the leaching rate expression.

- The cyanide consumption subsystem (only present in gold subsystem) calculates the amount of cyanide consumed by gold and other metals from stoichiometry and the leaching rate expression (leaching subsystem).

The total amount of time over which the simulation is conducted can be specified. It runs in specified time steps and simply terminates when it reaches the specified total simulation time.

CASE STUDY

The model was tested against data obtained from a South African CIP plant. The solids feed rate was 300 tons per hour and the carbon inventory was 3.8 tons per stage, ten percent being transferred every 45 minutes. The concentrations of metals other than gold, lumped as M, were 500 and 100 parts per million respectively, in the solids and the liquid entering the plant. Table 1 lists the "steady state" gold and cyanide profiles through the plant.

Table 1 – Plant data, parts per million

Stage	$[Au(CN)_2^-]$	Au on carbon	Au in solids	$[CN^-]$
Feed	5.3	—	—	
1	1.12	3500	3520	
2	0.35	1300	922	
3	0.06	500	310	
4	0.02	400	183	
5	0.01	300	165	
6	0.009	200	155	50
Feed	—	150	155	—

The simulation was run for long enough to reach "steady state", the criterion for which was that the concentration-time profiles in each stage were the same, to within a specified tolerance, between successive carbon transfers. The parameter estimation tool of Simulink was used to find sets of leaching and adsorption parameter values that minimized the sum of the differences between the final time-averaged concentrations in each stage, between carbon transfers, and the plant data in Table 1. *Table 2* lists the values obtained for the model parameters. *Table 3* shows the resulting model predictions alongside the data. *Figure 1* shows how the simulation developed the carbon profiles, starting with no gold on the carbon at time zero.

Table 2 – Model parameter values

Metal	k_A	K_A	k_L	K_L
Au	$5.5 \times 10^{-7} \, s^{-1}$	17000	$8.61 \times 10^{-7} \, s^{-1}$	399
M	$5.5 \times 10^{-7} \, s^{-1}$	17000	$1.6 \times 10^{-6} \, s^{-1}$	800

Table 3 – Actual and predicted profiles, parts per million

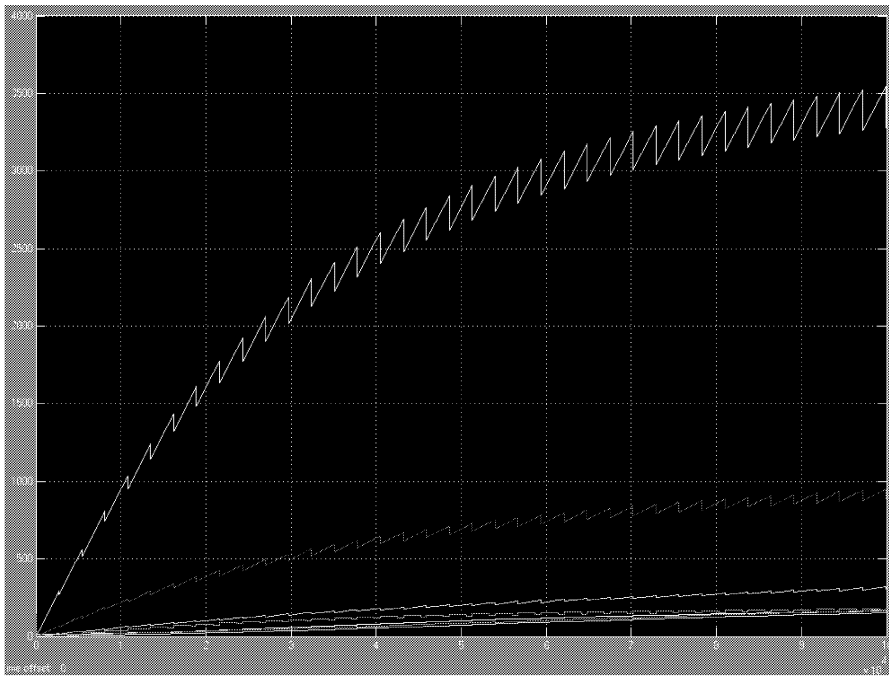| Stage	[Au(CN)$_2^-$]		Au on carbon		Au in solids		[CN$^-$]	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model
Feed	5.3	5.3	—	—		1.2		680
1	1.12	1.25	3500	3520		0.45		121
2	0.35	0.325	1300	922		0.17		42
3	0.06	0.095	500	310		0.07		31.2
4	0.02	0.034	400	183		0.025		29.7
5	0.01	0.016	300	165		0.009		29.6
6	0.009	0.012	200	155	0.01	0.003	50	29.5
Feed	—	—	150	155	—	—	—	—

Figure 1 – Carbon profiles as the simulation approaches "steady state"
(Grams Au per ton carbon versus time in seconds)

SENSITIVITY ANALYSIS

Once the simulation has been made to fit the plant data, it can be used to study the effect of various fluctuations in operating conditions on the process. For example, the solid feed rate can be varied to determine what that would do to the carbon loading profiles and the concentration of gold in the barren solution.

The simulation was subjected to a step change in the liquid feed concentration. An increase of 20 % (5.3 to 6.36 g/t) at 400,000 s was investigated. The total simulation time was 1,000,000 s.

Figure 2 illustrates the system's response to the step change. Note that the step was induced once the system has reached an approximate steady state and that the barren solution concentration once again strives towards a steady value. This increased gold in the barren solution can be countered by an increase in the carbon transfer rate. In this example it was countered by increasing the transfer rate by 13% (reducing the transfer time of 2,700 s to 2,350 s) at 650,000 s.
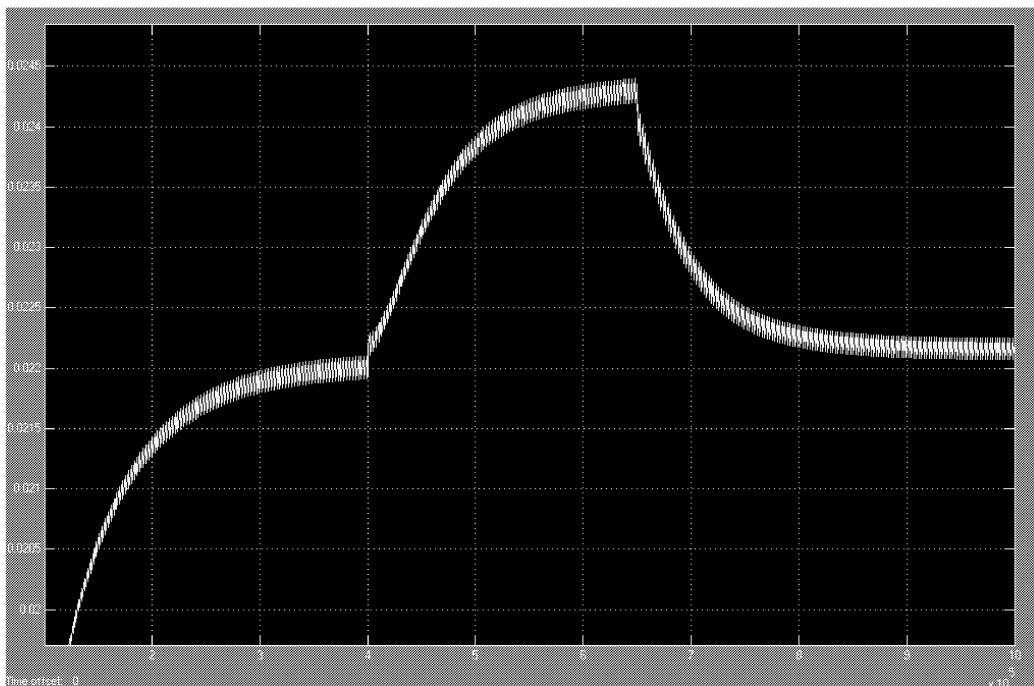

Figure 2 – Change in barren solution concentration when liquid feed concentration step is
countered with an increase in carbon transfer rate
(Grams Au per ton liquid vs. time in seconds)

DISCUSSION

While the staff of operating plants would probably need some assistance initially, especially with fitting suitable parameters for their particular plant data, setting up and running these simulations is easily learned. Simulink's graphical interface makes it easy to simulate situations of interest. The concept of simulation time makes Simulink ideal for unsteady-state problems, which plant operators face regularly. It will ultimately allow plant operators to achieve proactive and responsive control over their process. This is crucial for processes with large residence times, such as the CIP/CIL process.

Operators of CIP/CIL plants can now use this tool to examine the impact of various changes to their process. As they gain confidence in its predictions, they would naturally gravitate towards using this kind of simulation as a decision support tool and to diagnose process deviations. While it will never replace experience and sound judgment, a tool such as the one presented here can enable plant operators to consolidate their process knowledge and use it to train new people more rapidly, diagnose and solve problems more effectively, evaluate changes more rationally and generally gain substantially better control over the plant and process.

CONCLUSION

The work presented here set out to determine whether or not simplified linear rate and equilibrium equations representing the dissolution and adsorption of gold and competing metals can be used to build useful simulations of CIP/CIL plants, without separate experimental work to quantify the constants needed. The outcome is that this is indeed possible. Simple empirical linear equations, built into Matlab Simulink, generate realistic simulations of the dynamic behaviour of CIP/CIL plants.

The enhanced understanding that proper use of a simulation tool such as the one presented here will generate will ultimately enable the plant staff to operate "closer to the wind" without making costly errors, thereby recovering gold more cost effectively and so running a more powerful money machine.

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