

REAL-TIME OPTIMIZATION APPLIED TO GOLD CYANIDATION

L.R.P. de Andrade Lima¹ and D. Hodouin²

¹Federal University of Bahia - Department of Materials Science and Technology
Rua Aristides Novis, 2, Federação, Salvador, Bahia, Brazil, 40210-630 - lelo@ufba.br

²Laval University - Department of Mining, Metallurgy and Materials
Quebec, Canada, G1K 7P4 - daniel.hodouin@gmn.ulaval.ca

ABSTRACT

In this study, a phenomenological dynamic model of gold ore cyanidation in agitated tanks is derived and calibrated with a set of industrial data. The model is used to simulate the dynamic behavior of a three-tank industrial plant and to test the performance of the uncontrolled plant, a feedback control system and a real-time optimization strategy. The results for the open loop circuit (uncontrolled plant) show large losses of gold at low cyanide consumption. The regulatory control of the cyanide concentrations in the first tank helps in improving the economic efficiency. The optimal strategy is able to keep the three cyanide control loops at their optimal set points in order to cope with the disturbances and minimize an economic objective function containing both the cyanidation cost and the gold losses.

INTRODUCTION

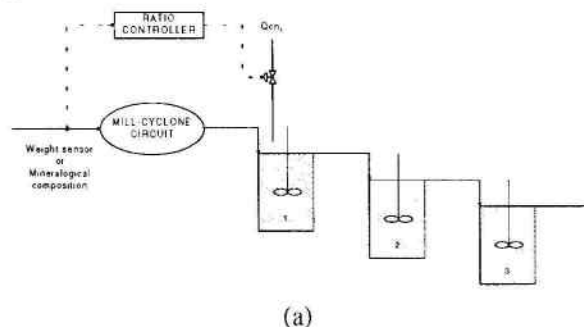
Process control applied to gold cyanidation plants is relatively new, despite the availability of sensors for pH, solid content and dissolved oxygen measurement, because the instruments to measure the critical operational variables, such as the free cyanide content, were developed only during the 1980's [Brandt *et al.*-1986, Wyllie-1987, Uys *et al.*-1987, Crundwell-1991, Ingles, and Rowden-1997], while the measurement of the solid and liquid gold contents are not yet currently used [Brandt *et al.*-1980, and Victor *et al.*-1982].

Feedforward adjustment of cyanide addition is the first usual control practice in a cyanidation plant; the cyanide flowrate is set proportionally to the ore feedrate or scheduled according to the ore type. A second usual approach is feedback control with PI controller (proportional and integral actions), to maintain the reagent concentration in some of the tanks at constant values [Flintoff-1993, Dufresne *et al.*-1994, and Caron *et al.*-1999]. However the ore feed composition as well as its texture is continuously disturbed. Thus, the

cyanide content feedback control loops necessarily create variations of the reagent consumption and gold recovery, factors that have a direct impact on the profitability of the operation.

When a flotation circuit precedes a cyanidation circuit, for instance in the processing of copper- gold ore, the feed stream is usually instrumented with a metal content analyzer. Thus, a feedforward strategy can be sometimes used to compensate for feed disturbances [Pelletier-1999]. Figure 1 summarizes the strategies employed nowadays in cyanidation plants.

Real-time optimization (RTO) is a control technique, based on process mathematical models and optimization algorithms, designed for maintaining a plant at its optimal operating regime. This technique has been developed in the 70s and became mature in the 90s, due to the improvement of computer power, the development of efficient optimization algorithms and the increase of the market competition [Marlin and Hrymak-1997]. For these reasons, this control strategy is attractive for chemical and petrochemical industries that look for an increase of plant performance. It has a positive impact on the fabrication cost of the product or on the profit margin. In spite of the relatively limited instrumentation available in the gold hydrometallurgy plants, real-time optimization seems to be an attractive option to be assessed.



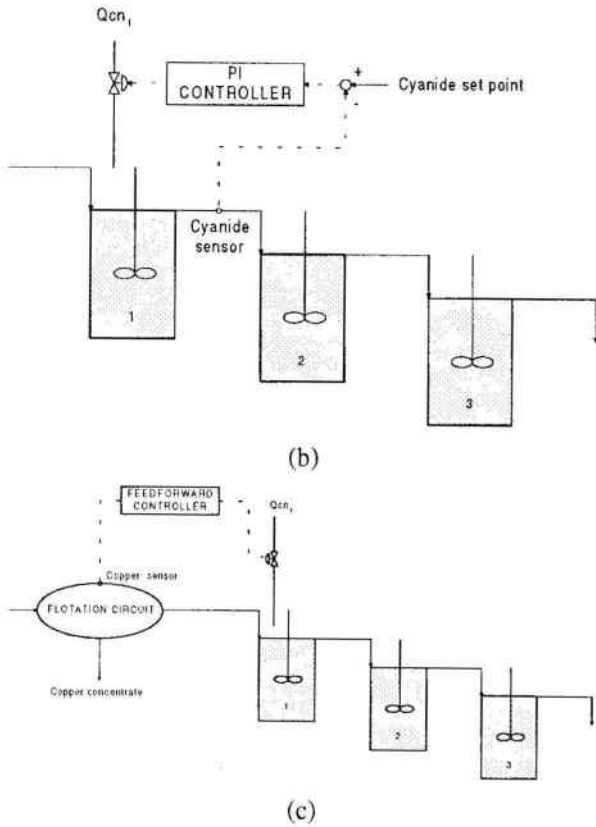


Figure 1: Industrial cyanide control strategies: a) ratio control, b) feedback control, c) feedforward control.

DYNAMIC MATHEMATICAL MODEL

To assess the validity of RTO strategies before their application to industrial processes it is important to develop of a realistic model to simulate the process behavior. A dynamic model of gold ore cyanidation in agitated tanks is derived using the liquid, solid and chemical species material balance equations for a continuous three-phase agitated reactor, assumed perfectly mixed and with constant pulp volume, as shown schematically in figure 2.

The model consists of seven algebraic-differential equations expressing the dynamic mass balance equations for each tank, and other physical relationships. They are:

- Ore mass balance:

$$\frac{dM_{s_i}}{dt} = Qs_{i-1} - Qs_i$$

- Liquid mass balance:

$$\frac{dM_{l_i}}{dt} = Ql_{i-1} - Ql_i$$

- Mass balance of gold in the ore:

$$\frac{d[M_{s_i}Cs_i]}{dt} = Qs_{i-1}Cs_{i-1} - Qs_iCs_i - M_{s_i}RAu_i$$

- Mass balance of gold in the liquid phase:

$$\frac{d[M_{l_i}Cl_i]}{dt} = Ql_{i-1}Cl_{i-1} - Ql_iCl_i + M_{s_i}RAu_i$$

- Mass balance of cyanide in the liquid phase:

$$\frac{d[M_{l_i}Ccn_i]}{dt} = Ql_{i-1}Ccn_{i-1} - Ql_iCcn_i + Qcn_i - M_{l_i}RCN_i$$

- Constant volume of slurry in the tanks:

$$\frac{M_{s_i}}{\rho_s} + \frac{M_{l_i}}{\rho_l} = V_i$$

- Perfect mixing conditions:

$$\frac{M_{s_i}}{M_{s_i} + M_{l_i}} = \frac{Qs_i}{Qs_i + Ql_i} = Cw_i$$

In the above equations, M_s is the ore hold up, M_l the liquid hold up, Q_s the ore flow rate, Q_l the liquid flow rate, C_s the gold concentration in the ore, C_l the gold concentration in the liquid, C_{cn} the cyanide concentration in the liquid, C_w the solid concentration in the pulp, V the net reactor volume, Q_{cn} the cyanide flowrate added in the tank, RAu the rate of gold dissolution, RCN the rate of cyanide consumption and ρ_s and ρ_l are respectively the ore and liquid densities.

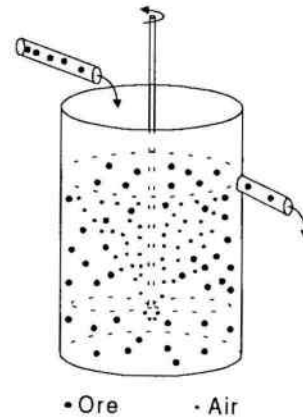


Figure 2: Three-phase agitated reactor

The kinetics of the three-phase reactions are complex due to the multiple steps involved for the reactants and products, such as mass transfer, diffusion and reaction. A population balance approach should be used considering the spectrum of properties of the particles, however for the present purpose, the pseudo

homogeneous hypothesis is sufficient to identify trends for RTO techniques. For gold leaching, the kinetics may be empirically described as an order α process with respect to gold concentration and an order one with respect to cyanide concentration, as in the following equation :

$$R_{Au_i} = k C_{cn_i} (C_{s_i} - C_{sf})^\alpha$$

where k is the rate constant, C_{cn} the cyanide concentration in the liquid, C_s the gold concentration in the ore, C_{sf} the residual gold concentration in the ore, and α the reaction order for gold.

The kinetics of cyanide consumption is empirically described by two superimposed effects. The first one explains the constant velocity cyanide consumption by cyanicides, such as copper and iron minerals, and the second explains the cyanide consumption effect proportional to the cyanide content, such as the losses by hydrolysis to hydrogen cyanide and ammonia, and the oxidation to cyanate or cyanogen [Adams-1990]. The rate of consumption is then:

$$R_{CN_i} = e + f C_{cn_i}$$

where C_{cn} is the cyanide concentration in the liquid, e is the rate constant of order zero, and f the rate constant of order one.

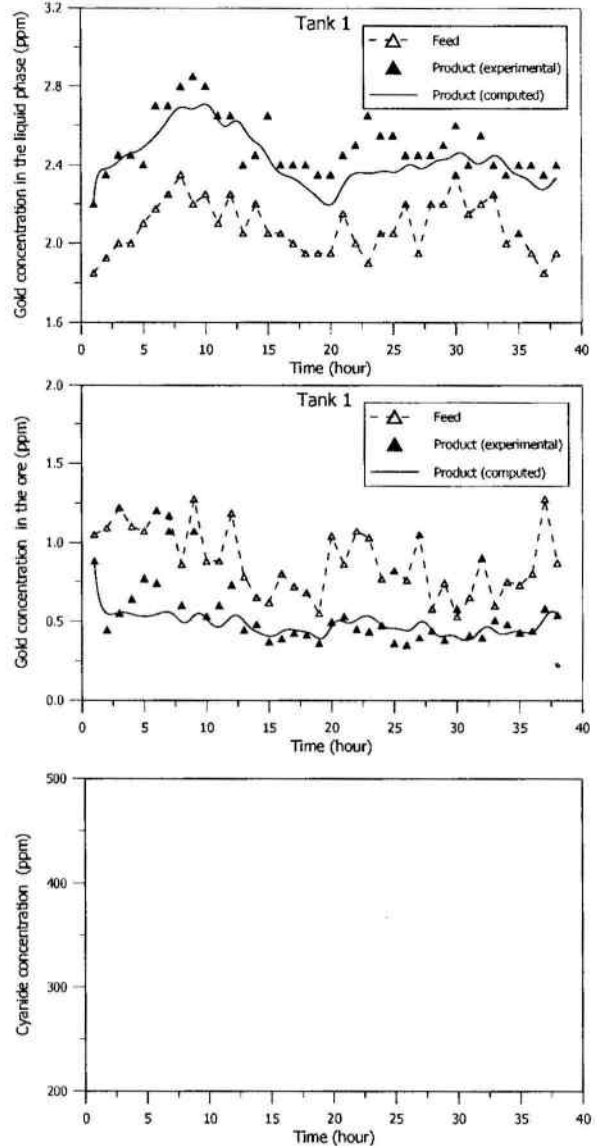
This simulation model for an industrial circuit leads to an algebraic-differential system of non-linear equations, which may be numerically solved by the fourth order Runge-Kutta method after some algebraic manipulations.

The model was calibrated with a 38-hour dynamic data sets from an industrial three-tank plant [De Andrade Lima-2001]. The kinetic parameters of the model and the effective reactor volume, shown in Table I, were estimated by a least-squares method using the modified simplex search method [Nelder and Mead-1965].

Table I: Model parameters

α	2.15	-
k	5.50×10^3	$[(t_{sol}/g_{Au})^{\alpha-1} (t_{liq}/g_{CN})/h]$
e	3.43	$[g_{CN}/(t_{liq}h)]$
f	1.47×10^2	$[1/h]$
V_t	1.16×10^3	$[m^3]$

As shown in figure 3, the model is sufficiently accurate to simulate the dynamic behavior of the cyanidation plant, which was used for calibration, and can be used to assess the performance of control strategies for this specific plant.



REAL TIME OPTIMIZATION

The hierarchical scheme presented in figure 4 is proposed for the optimizing control of a cyanidation plant. It optimally controls the cyanide distribution in the three tanks (Q_{cn}) to compensate the following feed disturbances: changes in solid flowrate (Q_s), liquid flowrate (Q_l), solid gold content (C_s), liquid gold content (Cl) and liquid cyanide content (C_{cn}). At the supervisory level a steady state version of the tank-leaching simulator is used to optimize an economic objective function. At the lower level the control loops are used to track the cyanide content set points selected by the optimizer.

The circuit economic performance depends upon antagonistic indices: the gold loss in the plant tail, the cyanide consumption and the residual cyanide concentration in the plant tail. Cyanide addition increases the process costs (reagent cost plus cyanide destruction cost in the plant tail) but decreases the gold loss. In the present study, the economic function to be optimized is composed of the gold loss and cyanide consumption weighted by their relative prices (respectively 10 US\$/g and 1.35 US\$/kg). The cyanide destruction cost has not been included in the criterion, because the economic impact of the tail cyanide concentration on the destruction cost is not well documented. The optimum operating conditions of the plant is determined by a gradient conjugate directions optimization method [Powell-1964].

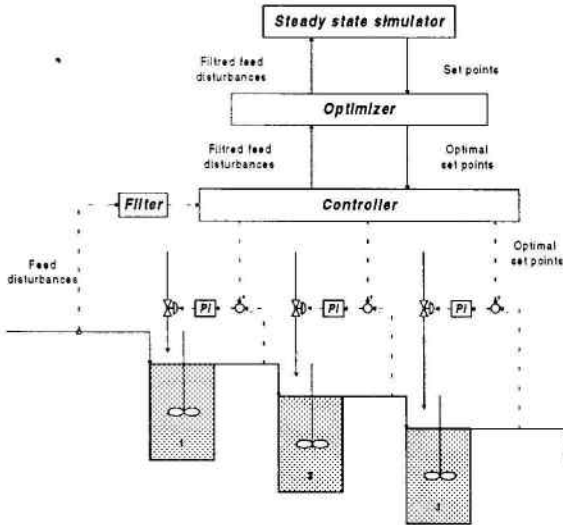


Figure 4: Scheme of the real-time optimization of the three-tank cyanidation plant.

RESULTS AND DISCUSSION

The plant was simulated for 300 hours and feed disturbances are sequentially happening at times 100, 150, 200 and 250 hours as shows figure 5.

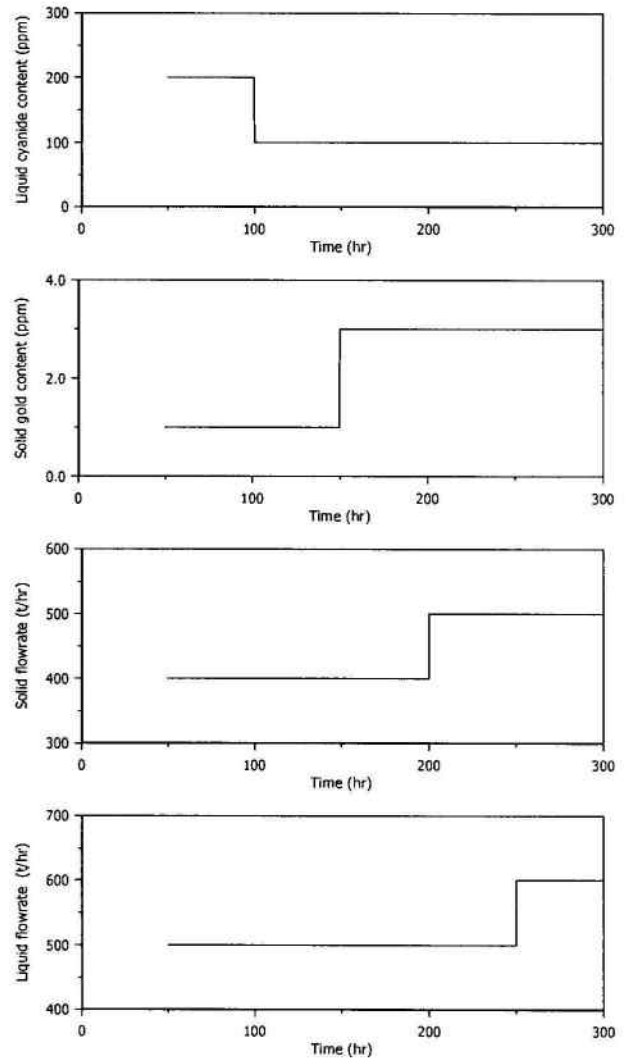


Figure 5: Feed disturbances

Three different operating strategies were simulated: the open loop circuit (uncontrolled operation), the feedback control of cyanide consumption in a single loop, and the optimal feedforward strategy described above. Figures 6 and 7 show the gold and cyanide concentrations in the three tanks, while figures 8 to 10 show the cyanide flowrates added into each tank. Finally, figure 11 shows the optimal set points of cyanide concentration for each tank.

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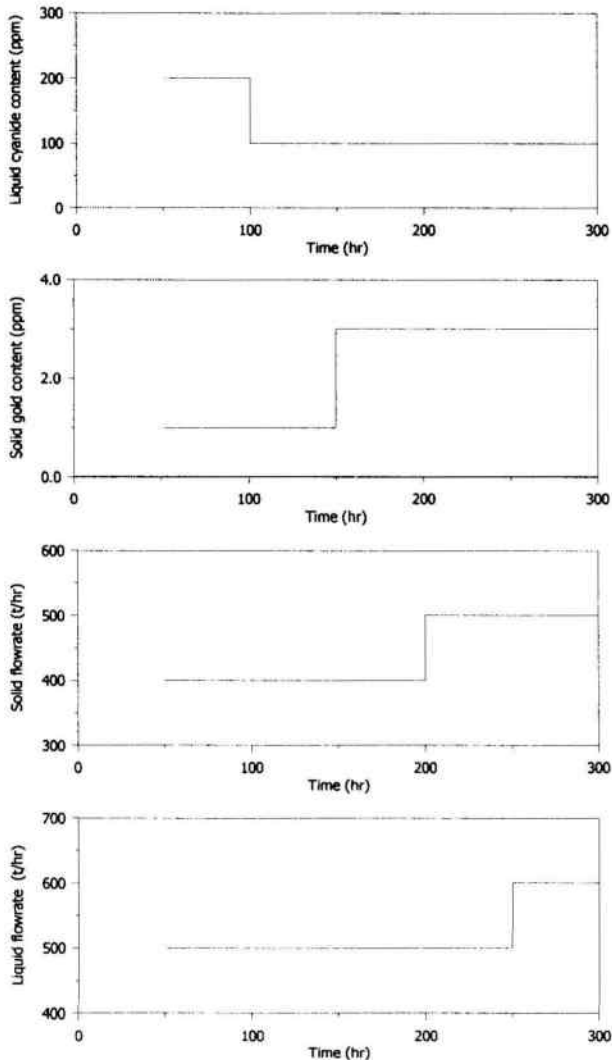


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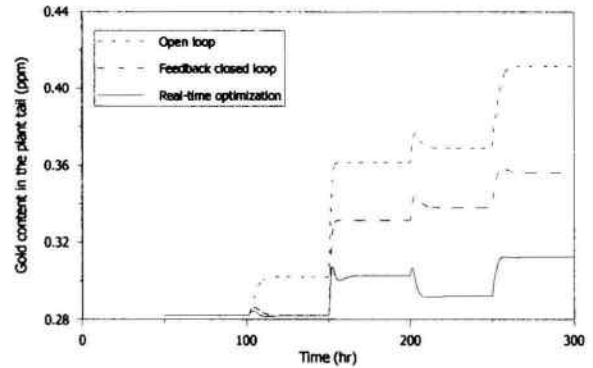


Figure 6: Gold concentrations in the tanks

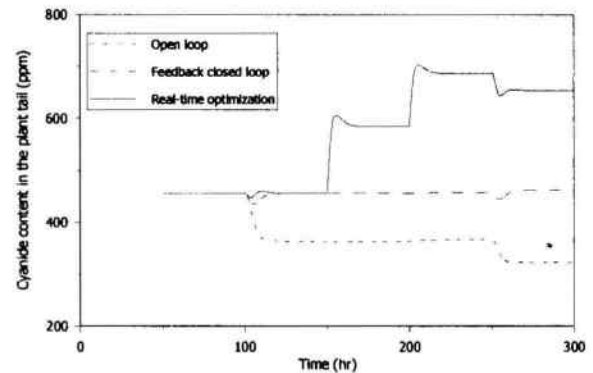


Figure 7: Cyanide concentrations in the tanks

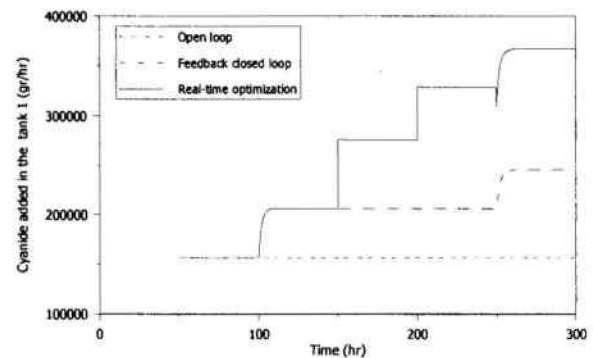


Figure 8: Cyanide addition flow rate in the first tank

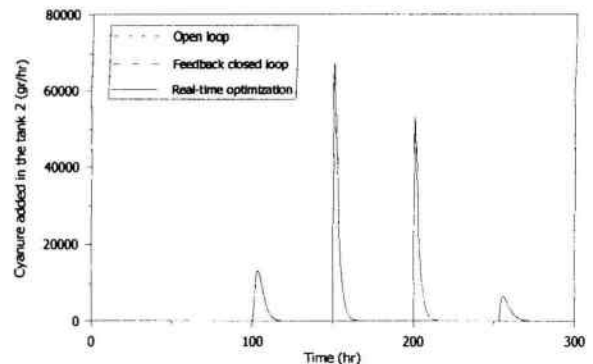


Figure 9: Cyanide addition flow rate in the second tank

Table II: Metallurgical performance indices

		Operating strategy		
		Open loop	Feedback closed loop	Real time optimization
Metallurgical Performance indices	Gold loss (g/h)	153	141	130
	Cyanide added (kg/h)	218	265	331
	Cyanide to be destroyed (kg/h)	195	237	297
Weighted criterion (US\$/h)		3505	3447	3424

CONCLUSIONS

Dynamic simulation of a cyanidation plant is used for comparing three different operating strategies of a disturbed plant. For the type of disturbance evaluated (feed cyanide and gold contents variations and ore and water feed rates variations), it is shown that a very significant improvement of the process economics can be obtained by feedback control of the cyanide addition, at constant first tank concentration set point. Furthermore, if it would be possible to measure the circuit feed property, including its gold content, an additional improvement of the revenue could be obtained by the application of an optimal feedforward controller of the cyanide set points. In addition to the feed instrumentation requirement, this real time optimization strategy requires a leaching model. In practice this model should be adapted on-line to take account of possible changes of the ore nature.

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