Available online at www.sciencedirect.com

SCIENCE DIRECT®

Minerals Engineering 18 (2005) 671–679

MINERALS ENGINEERING

This article is also available online at:
www.elsevier.com/locate/mineng

Optimization of reactor volumes for gold cyanidation

L.R.P. de Andrade Lima *, D. Hodouin

Department of Mining, Metallurgy and Materials Engineering, Laval University, Quebec City, Canada G1K 7P4

Received 10 November 2004; accepted 9 December 2004

Abstract

The mineral industry has been using cyanidation of aerated slurries to recover gold from ores for more than a century. However, the leaching plant is usually designed as a series of agitated tanks of the same size, without any attempt to find an optimal plant design for improving the circuit efficiency, either by decreasing the cyanide consumption, or increasing the gold recovery, or decreasing the total plant volume. The objective of the study is to test, by simulation, if it would be profitable to use plant designs differing from the usual ones. The focus is put on the selection of the volumes of the tanks in the cascade of leaching reactors. The methodology involves the use of gold dissolution and cyanide consumption kinetic models incorporated into a simulator, and the definition of a performance criterion for the plant optimization. The performance is characterized by a cost function containing a term representing the value of the unleached gold and a term accounting for the cyanide consumption costs. It is shown that, for the same total volume, using a sequence of increasing size reactors improves the performance of the plant. The results are produced for different size of the ore particles and different numbers of tanks in the leaching circuit.

Keywords: Cyanidation; Gold ores; Leaching; Modelling; Process optimisation; Process synthesis

1. Introduction

Leaching of ores by cyanide in aerated alkaline slurries has been the dominant process for gold extraction for more than one century. In order to accelerate the gold recovery, in most of the high-grade ore plants, the cyanidation process occurs continuously in a cascade of large agitated tanks. The reactor volume optimization is a relevant problem that has been studied for many chemical systems; however, hydrometallurgical reactors have received much less attention. This is particularly true for the leaching tanks that are of interest in this paper.

It is widely accepted that pure gold cyanidation is an electrochemical process, where gold is oxidized and then complexed to the stable ion $[Au(CN)_2]^-$, and oxygen is reduced and hydrogen peroxide decomposed (Habashi, 1987; Yannopoulos, 1991; Marsden and House, 1992). A typical gold ore processing plant is composed of the following sequence of unit operations: ore comminution, size classification, gravity concentration, and slurry dewatering, followed by gold leaching and gold recovery on activated carbon or by zinc precipitation, and finally gold elution, electrolytic extraction, melting and casting. The major reactants in the gold leaching process are cyanide and oxygen, but also sodium hydroxide is used to control pH, and sometimes lead nitrate is used to control cyanide consumption by sulfides.

In a conventional cyanidation process, high cyanide concentrations in large tanks are used to improve gold

* Corresponding author. Present address: Department of Chemical Engineering, M.H. Wong Building, McGill University, 3610 University Street, Montreal, Canada H3A 2B2. Tel.: +1 514 398 5170; fax: +1 514 398 6678.

E-mail address: ldeand@po-box.mcgill.ca (L.R.P. de Andrade Lima).

0892-6875/$ - see front matter
doi:10.1016/j.mineng.2004.12.007

Nomenclature

Ccn	cyanide concentration in the liquid (mg/kg)
Cl	gold concentration in the liquid (mg/kg)
Co	oxygen concentration in the liquid (mg/kg)
Cs	gold concentration in the ore (mg/kg)
Cw	solid concentration in the pulp (g/g)
Cs_∞	residual gold concentration in the ore (mg/kg)
$\bar{d}$	average size of the ore particles (μm)
J	cost function ($/h)
Ml	liquid hold up (kg)
Ms	ore hold up (kg)
N	number of reactors in the cascade
Pr_{CN}	price of cyanide ($/kg)
Pr_{Au}	price of gold ($/g)
Qcn	cyanide flow rate added (kg/h)
Ql	liquid flow rate (kg/h)
Qs	ore flow rate (kg/h)
r_{Au}	dissolution rate of gold (mg/kg h)
r_{CN^-}	rate of cyanide consumption (mg/kg h)
r_o	rate of oxygen consumption (mg/kg h)
r'_o	rate of oxygen feed (mg/kg h)
V_i	net volume of the ith reactor in the cascade (m^3)
V_T	total net volume of the reactor cascade (m^3)

Greek symbols

ρs	ore density (g/cm^3)
ρl	liquid density (g/cm^3)
τ	average residence time (h)

Subscripts

0	first reactor of the cascade
i	ith reactor of the cascade
N	last reactor of the cascade

leaching rate and gold recovery, but at the same time this practice is responsible for high cyanide consumption and investment (Kondos et al., 1995; de Andrade Lima, 2001; de Andrade Lima and Hodouin, Submitted for publication). A compromise between these two antagonistic effects is required for gold leaching plant performance optimization. Optimal reactor design and optimal operating conditions tuning are attractive techniques for such a process, to improve profitability in a context of strongly competitive markets, tight product specifications and tough environmental regulations (Levenspiel, 1999; Edgar and Himmelblau, 1988; Chitra and Govind, 1985; Biegler et al., 1997).

The determination of the minimum volume configuration of a cascade of continuous stirred tank reactors (CSTRs) is a particular problem, in the field reactor optimization, which was first pointed out by Denbigh (1944) and subsequently applied to various chemical systems (Leclerc, 1953; Aris, 1961; Kubota et al., 1961; Szépe and Levenspiel, 1964; Wood and Stevens, 1964; Luss, 1965; Crooks, 1966; Floquet et al., 1985; Lopes and Malcata, 1993). The problem of the optimum design of the reactor sizes in a cascade of CSTRs is mathematically defined as follows:

$$\begin{cases} \min\limits_{\mathbf{V}} \quad f(\mathbf{V}) \\ \text{s.t.} \\ V_i \geqslant 0 \\ \sum\limits_{i=1}^{N} V_i = V_T \end{cases} \tag{1}$$

where f is an objective function, such as the conversion of a reactant or product, $\mathbf{V}$ is the vector of the net volumes of the tanks in the cascade V_i, and V_T is the total net volume of the cascade. The minimization problem given by Eq. (1) can be solved using dynamic programming or direct optimization methods, such as the conjugate or the reduced gradient methods (see Bellman, 2003; Edgar and Himmelblau, 1988; Wang and Fan, 1964).

Three systematic optimal design studies of the volumes in a cascade of leaching reactors are available. The first one (Henein and Biegler, 1988) minimizes the residence time for a given conversion degree, in a cascade of reactors for leaching reactions that follow a shrinking core kinetic model. In the case of leaching under surface-reaction control, the ideal volumes in the cascade of CSTRs depend on the targeted solid conversion, but always decrease from the first to the last reactor. For a conversion of approximately 99.5%, the ratios V_i/V_T in the case of four CSTRs are 0.314, 0.269, 0.226, and 0.187, and for very low conversion the ratios are approximately 0.25. In the case of leaching under pore-diffusion control, the ideal volume ratios also depend on the solid conversion: for approximately 99.5% conversion the ratios V_i/V_T for four CSTRs are 0.205, 0.295, 0.285, and 0.215, and for 80% conversion the ratios are 0.13, 0.23, 0.30 and 0.34. The second study (Papangelakis and Demopoulos, 1992; Papangelakis and Luus, 1993) deals with pressure oxidation. The performance index is the conversion multiplied by the ratio of the time for complete conversion to the mean residence time. This index tends to maximize the conversion while minimizing the plant volume, and, when the ore residence time in the reactor is sufficient for complete leaching, it reduces to the ore leaching conversion. The