Minerals Engineering 101 (2017) 47–57

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Comparative assessment of heap leach production data – 1. A procedure for deriving the batch leach curve

Petrus J. van Staden [a,*], Andrei V. Kolesnikov [b], Jochen Petersen [c]

[a] *Mintek, 200 Malibongwe Drive, Randburg, South Africa*
[b] *Department of Chemical and Metallurgical Engineering, Tshwane University of Technology, Pretoria, South Africa*
[c] *Department of Chemical Engineering, University of Cape Town, Rondebosch, South Africa*

ARTICLE INFO

Article history:
Received 31 August 2016
Revised 17 November 2016
Accepted 21 November 2016
Available online 30 November 2016

Keywords:
Heap leaching
Batch curve
Kinetics
Laboratory columns
Commercial heaps

ABSTRACT

A method is provided for deriving the average macro-scale batch leaching kinetics of ore on a commercial heap on which portions of the heap (or cells) possess a range of leaching ages due to irrigation commencing while stacking is still in progress. It has been designed to require as only inputs the average ore grade, daily amount of ore stacked and the rate of metal extraction to a common drainage collection point for all cells.

A comparison of the batch curve, thus derived, with the batch curve upon which the design of the pad footprint was based provides an early indication of the likelihood of reaching the desired rate of metal production. Furthermore, any attempt to fit the performance of a leaching model to that of a commercial heap requires the description of heap leaching kinetics in the form of a batch curve, since leaching models typically produce batch curves as simulation outputs.

The procedure relies on the selection of a functional form, denoted $X_i(t)$, to describe the macro-kinetic batch extraction curve from a single cell (or part thereof) on a heap. Summation over time of the contributions to production from all cells stacked up to time t, assuming each cell leaches according to $X_i(t)$, yields a calculated production graph. The parameters of the function $X_i(t)$ are adjusted to minimise the sum of squared residuals between observed and calculated production graphs. $X_i(t)$ thus found defines the batch curve sought. The procedure can be implemented on a spreadsheet and can be applied to both the rate of valuable target metal extraction and the rate of reagent consumption.

In a subsequent paper the application of the method on commercial heap leaching production data will be demonstrated. From the optimised parameters in $X_i(t)$ conclusions can be drawn about the efficiency of wetting of the ore, the relative rate of leaching and the diffusional restriction to reagent supply to the mineral surface.

1. Introduction

1.1. Background

The leach curve is central to the design specification of the footprint of a heap leach pad that is necessary to meet the required target metal production rate, and ultimate extent of extraction, (which in turn is determined by the period of time that the ore will remain under irrigation), for a given ore grade.

During heap leach test work, the ore under consideration is loaded into columns or cribs and irrigated with leach solution. From the volume and metal content of the drainage solution collected daily, the cumulative extent of metal extraction is calculated as a function of time. In the laboratory arrangement all the ore contained in the column is subjected to the same period of leaching, and the graph of cumulative metal extraction versus time will constitute the ‘batch curve’. The concentration profiles existing over the height of the column means that not all the ore is subjected to the same leaching conditions, therefore it is advisable to perform the laboratory experiments in columns of the same height as that ultimately intended for the commercial heaps. The premise is by meeting these requirements the laboratory column represents a small vertical segment of the commercial heap.

Abbreviations: Cor., Pearson correlation coefficient; GAC, Gangue Acid Consumption; FBC, Fitted Batch Curve; SSR, Sum of Squared Residuals.

* Corresponding author.

E-mail address: petrusv@mintek.co.za (P.J. van Staden).

http://dx.doi.org/10.1016/j.mineng.2016.11.009

Nomenclature

Symbols

a_1 *to* a_4	constants in Eq. (17)
A	surface area, m^2
C_i	concentration of species *i*, mass fraction
C_i^0	initial concentration of species *i*, mass fraction
F_{step}	tracer concentration normalised with respect to background concentration and pulse input concentration, unitless
F	rate of flow, m^3/d
H	height, m
$PIB_{n,i}$; $PCS_{n,i}$; $PDS_{n,i}$	integrals defined by Eqs. (11)–(13), with respect to species *i*, from the time period that started at the time indexed by *n* up to the current time, tonne
K	pre-exponential kinetic rate constant in Eq. (3) and in the relation proposed by Ghorbani et al. (2013), reproduced in Eq. (8), d^{-1}
$\dot{W}$	rate of stacking of ore, t/d (dry basis)
$P_i(t)$	extent of extraction of species *i*, a function of time representing the true batch curve according to which the ore on a heap is leaching, mass fraction
s_i	constant terms appearing in Eqs. (5) and (6)
t	time, days
W_n	mass of ore stacked by time indexed by a number *n*, tonne
W_{abc}	mass of species identified by the alphabetic label *abc*, tonne
V	volume, m^3
$X_i(t)$	extent of extraction of species *i*, a function of time fitted to production data to approximate the true batch curve $P_i(t)$, mass fraction

Greek symbols

α_x	mass fraction of mineral that is liberated and reactive to the lixiviant in the relation proposed by Ghorbani et al. (2013) which is reproduced in Eq. (8)
β	a term in the rate expression used by Ghorbani et al. (2013), which is not used in this work
κ_0	pre-exponential constant in Eqs. (9) and (10)
κ_1	exponent in Eqs. (9) and (10)
κ_x	mass fraction of mineral that is liberated and reactive to the lixiviant in Eqs. (9) and (10)
κ_w	mass fraction of heap that is effectively contacted with leach solution in Eqs. (9) and (10)
$\kappa_x\ \kappa_w$	the extractable mass fraction of the species being leached in Eqs. (9) and (10)
θ	the duration of time for which an incremental quantity of ore has been irrigated/leached, d
ρ	bulk density, t/m^3 dry basis
φ	exponent in kinetic rate expression of Ghorbani et al. (2013), reproduced in Eq. (8), unitless
τ	mean residence time or "space-time", d

Subscripts and accents

$\dot{W}, \dot{X}_i(t)$	newtonian convention is used to indicate the derivative with respect to time for these two variables
i	indicates the species in question
0, 1,2,… n	time index
a, b	time indexes to represent any time $t_1 \leqslant t_{a,b} \leqslant t_2$ where $t_b > t_a$

The generated laboratory batch curve is never adopted directly as a design criterion for scale-up to commercial operation. Instead some form of experience-based empirical safety factor is applied. For example, for the design of copper heap leach plants the extent of extraction obtained in the laboratory could be multiplied by 0.9, and/or the time required for achieving a given extent of extraction under commercial conditions is taken as 50–100 percent more than the time required in the laboratory columns, according to Jansen and Taylor (2002). Other authors that comment on copper heap leaching scale-up include Miller and Newton (1999) who propose that chemical reaction kinetics need not be considered during modelling of the heap leaching of oxide-copper ores since the process is entirely mass transfer controlled and for scale-up of column leaching data suggest that the copper extraction obtained in columns be discounted by 5 percent. They further comment on the greater difficulty of extrapolating gangue acid consumption results, and the importance of only estimating the acid consumption based on data obtained from columns at the full height of the intended commercial heaps. John (2011) remarks that the rate of heap leaching of higher-grade ores tend to be limited by the rate of irrigation and reagent supply, while those of lower-grade ores are more likely to be controlled by mass transfer in the heap. His rule of thumb for the scale-up of column leaching data for base metal and gold extraction is to assume the commercial heap will achieve 80 percent of a given extent of extraction over a time period three times as long as that observed in laboratory columns. Kappes (2002), in referring to gold and silver heap leaching applications, points out that the leaching kinetics observed in laboratory columns is always faster than that of commercial heaps. He does not offer scale-up factors between column leaching and commercial leaching kinetics, but remarks that while theoretically the application of 0.8 tonne of irrigation solution per tonne of ore should yield 95 percent gold/silver extraction, the requirement in commercial practice is typically about 1.3 tonne solution per tonne ore. Taking laboratory column leaching to closely approximate the theoretical ideal, it implies that the commercial heap leach cycle would be 1.6 times longer than that of column leaching to reach 95 percent extraction under a given irrigation rate. These rules rely on generalisation of trends observed on past experience, which is currently the best recourse available to design engineers. However, methodologies for placing scale-up on a more fundamental footing would be welcomed by the industry. The ability to convert commercial production data to an equivalent batch curve as facilitated by the method provided here would ease comparisons between laboratory and production data for future scale-up studies.

1.2. The problem addressed

Commercial heap leaching practice differs from the batch leaching in laboratory columns in that it is a more continuously operated system. It is common for the heap stacked on a commercial leach pad to be sub-divided into cells. While it may require a few months to stack all the ore on a heap, a cell may be defined by the amount of ore stacked in a few days.

Referring to the example of acid heap leaching of oxide-copper ore, after crushing the ore is typically contacted with concentrated acid in the agglomeration drum for 'curing', as a means to rapidly deactivating the most reactive acid consuming gangue minerals and initiating leaching of the valuable metal. The curing reactions occur between the time of agglomeration/stacking and the time when irrigation is initiated, which dilutes and rinses whatever curing acid remains. The acidic heap leaching of uranium ore could