



Modeling the performance of pyritic biooxidation heaps under various design and operating conditions

Sylvie C. Bouffard ^{a,*}, David G. Dixon ^{b,2}

^a Barrick Technology Centre, 323 Alexander St., Vancouver, BC, Canada V6A 1C4

^b Department of Metals and Materials Engineering, The University of British Columbia, 309-6350 Stores Road, Vancouver, BC, Canada V6T 1Z4

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ABSTRACT

The pyrite heap biooxidation model discussed in the first paper of this two-part series was expanded to model the effects of heat generation, conduction, and convection within the heap and at its boundaries. The new sub-routine utilized parameters whose values are known to the user; the other sub-routines utilized the same parameters as in the first paper. The inclusion of the heat balance sub-routine significantly changes the pyrite oxidation profile, which is uniform in the vertical and lateral planes in an isothermal system, such as a column, but highly segregated in the vertical plane of a non-isothermal system, such as a heap. There are numerous phenomena at play in a non-isothermal system: at the top, faster cell growth and self-inhibition of the fines oxidation; at the bottom, evaporative cooling and oxygen depletion. A model sensitivity study revealed that, for a given sulfide head grade and particle size, the magnitude and duration of these phenomena can best be controlled by inoculating the heap with mesophiles, moderate thermophiles, and extreme thermophiles, increasing the aeration rate, and keeping the heap height as short as possible to achieve the fastest and most uniform oxidation throughout the heap.

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1. Introduction

Despite using sophisticated detection instruments in geological exploration, gold mining companies nowadays very rarely encounter rich oxidized gold deposits that will replenish their reserves for years to come. Rather these deposits tend to be of small size, and thus of greater appeal to junior mining companies, or if holding significant reserves or resources, will contain difficult-to-treat ores that may be single or double refractory, requiring pre- and post-treatment of the sulfidic and carbonaceous minerals. High-grade precious metal ores containing sulfide minerals are amongst the easiest refractory ores to treat by ambient or pressure leaching to oxidize the sulfide lattice. Low-grade ores do not justify the large capital and operating expense of such process equipment. The only economical means of oxidizing low-grade ores is by heap bioleaching, a technology unsophisticated in appearance, and having a large footprint in comparison to agitated tanks and autoclaves. The process consists of stacking ore onto a lined pad and irrigating the heap with a leaching solution containing iron, acid, and microorganisms

for at least one year. The principal chemical reactions are the oxidation of pyrite to ferrous, sulfur, and sulfate, the oxidation of elemental sulfur to sulfate, the oxidation of ferrous to ferric, and the precipitation of jarosite.

The most active period of research and development into heap biooxidation of refractory sulfide ores occurred in the mid 1990s, just before the low gold cycle of the early 2000s. Demonstration heaps ranged in tonnage from 1200 tonnes in Bulgaria for treatment of double refractory ores, to 4300 tonnes in South Dakota for sulfidic ores, and finally to 25,900 tonnes in Nevada for singly and double refractory ores (Bouffard and Dixon, 2004). The Bulgarian heap, which was not aerated, achieved an oxidation rate of 0.0018 wt.% sulfide/day, compared to 0.0031 wt.% sulfide/day in the aerated heap of South Dakota. The oxidation rate in the much larger non-aerated heaps in Nevada ranged from 0.0024 to 0.0059 wt.% sulfide/day, which, at its best performance, was nearly 3 times faster than the Bulgarian operation. Newmont's 800,000-tonne non-aerated heap trial followed in 1995, achieving a sulfide oxidation rate of 0.0033 wt.% sulfide/day. In 1996, Newmont also built a large-scale aerated heap, which was the precursor to their commercial heap biooxidation operation which began production in 2000. In 2003, Geobiotics commissioned a biooxidation heap at the Agnes Mine, stacking 4.6 t/h of pyrite/arsenopyrite gold concentrate coated onto 36.5 t/h of ore substrate. As the pyrite occurs as micron-size grains, the leached ore can be removed and treated for gold recovery only 60 days after the start of irrigation.

Successful commercial practice of heap biooxidation hinges on achieving the fastest sulfide oxidation rates, ensuring uniform oxidation

* Corresponding author. Tel.: +1 604 682 1730x222; fax: +1 604 682 1767.

E-mail addresses: sbouffard@barrick.com (S.C. Bouffard), dixon@interchange.ubc.ca (D.G. Dixon).

¹ Formerly Doctoral Candidate with the Department of Materials Engineering, The University of British Columbia, is now Sr. Metallurgist, Barrick Technology Centre, 323 Alexander St., Vancouver, BC, Canada V6A 1C4.

² Tel.: +1 604 822 3679; fax: +1 604 822 3619.

throughout the heap volume, avoiding hot spots within the heap, precluding the formation of elemental sulfur (or completely oxidizing the elemental sulfur formed) to minimize cyanide consumption in the subsequent cyanide gold leach, controlling iron precipitation, and ensuring that the heap remains permeable to solution and air as it must undergo three cycles (sulfide biooxidation, neutralization, and cyanide leaching for gold).

To meet these criteria, metallurgists have adopted one of two approaches: empirical or fundamental. The empirical approach suggests that a mathematical multi-variable empirical equation can be developed using data from several dozen column tests. The user supplies the values of the heap height, irrigation rate, ore grade, aeration rate, and any other parameters and instantly the model can generate the recovery vs time profile. The quality of the model predictions depends on the quantity and range of the parameters tested in columns. This model includes no fundamental or engineering principles. The empirical model is very popular in the industry. The fundamental approach begins with a conceptual representation of the reactive and transport phenomena occurring within the heap, expressing each mathematically in differential form and solving the equations numerically. Although the literature refers to 16 such models (Dixon, 2003), some of which are simpler than others, the fundamental approach has not gained widespread acceptance in the industry for the following reasons: the model uses many parameters, the values of some parameters are completely unknown to the user, the model depends on column tests to evaluate the unknown parameters, and the user may find it difficult and time consuming to set up the problem. An empirical model can usually be derived more rapidly than a fundamental model and is more readily usable. However, a fundamental model can more effectively simulate phenomena and their interactions that would occur in the field but not necessarily in columns. Amongst such phenomena is the chemical oxidation of pyrite, liberating large amounts of heat during the oxidation of sulfide to sulfate, and thereby autocatalyzing itself thermally. The rise in temperature that would occur in a heap is not seen in a column. The rise in temperature is also not well simulated by a water jacket maintaining the column at constant temperature. The rise in temperature could be simulated by a water jacket whose temperature is continuously adjusted, but the user still would not know to which temperatures the jacket should be set and on what schedule the temperature set points should be changed. This is where the fundamental model surpasses the empirical model. The fundamental model can also aid the interpretation of laboratory and pilot scale tests and is an inexpensive tool for rapidly evaluating the outcome of changing parameters without the need to run more columns.

These authors, together with Dr. Jochen Petersen, developed a fundamental model of heap leaching for chalcocite, covellite, pyrite, and sphalerite minerals, called HeapSim, over the period from 2001 to 2003. The model represents the important chemical, biological, and physical steps which might occur, in series or in parallel, from the microscale of the individual sulfide mineral grains to the macroscale of the entire heap and its surroundings. Our previous publication (Bouffard and Dixon, 2008) introduced all components of the model, except the thermal function reserved intentionally for this paper. The model includes: i) a kinetic model dependent on particle size, temperature, and reagent concentration for the leaching of sulfide grains from coarse particles, ii) a solute hydrodynamic model that consists of solutes being transported by advection into vertical plug flow channels, crossing over into stagnant lateral branches, and diffusing towards the end of the branches, iii) the injection of air and the absorption of oxygen into solution, and iv) the growth and death of microorganisms oxidizing ferrous and elemental sulfur. All simulations showed in our previous publication were done under isothermal conditions. Simulations in this paper are non-isothermal and require the inclusion of a thermal function affecting the solid, liquid, and gas phases of the heap. This function is described in the next section. The Results and discussion section presents non-isothermal simulations demonstrating how heap performance can be controlled before stacking and during leaching.

2. Modeling procedure

2.1. Enthalpy balance model

The specification of the reaction chemistry and stoichiometry, the formulation of the reactive and transport phenomena, and the definition of the chemical and biological rate equations that are all part of the HeapSim model were presented in detail in our previous publication (Bouffard and Dixon, 2008) and will not be repeated herein. The enthalpy balance model is of utmost relevance in this paper. A previous model developed by one of the authors (Dixon, 2000) constitutes the foundation of the enthalpy balance. Briefly, the model assumes the solid, liquid, and air phases to be in thermal equilibrium at any depth within the heap, and the air to be saturated in water vapor anywhere in the heap. The model is based on the principles of heat conduction, heat generation by chemical reaction, and heat advection by solution, dry air, and water vapor. From these considerations, a 1-D enthalpy balance may be written thus:

$$\frac{\partial T}{\partial t} = \left\{ \frac{k^H}{\rho^H C_p^H Z^2} \right\} \frac{\partial^2 T}{\partial \zeta^2} - \left\{ \frac{f_F G^F C_p^F - f_A G^A C_p^A}{\rho^H C_p^H Z} \right\} \frac{\partial T}{\partial \zeta} + \frac{(n+1) \int_0^1 Q(\xi, \zeta) \xi^n d\xi}{\rho^H C_p^H} \quad (1)$$

where

$$f_F = \frac{G^F - k_v (\psi|_{\zeta=0} - \eta_\infty \psi|_{\zeta=\infty}) + G^A (\psi|_{\zeta=0})}{G^F} \quad (2)$$

and

$$f_A = \frac{C_p^A + C_p^V \psi + \frac{d\psi}{dT}}{C_p^A} \quad (3)$$

where the superscripts H, F, A, and V refer to the heap, solution, air, and water vapour, respectively. The term on the left-hand side of Eq. (1) is the accumulation term. From left to right, the four terms on the right-hand side correspond to heat of conduction, the heat of liquid-phase advection, the heat of gas-phase advection, and the heat generated by reactions, respectively. The functional f_F in Eq. (1) incorporates boundary effects such as liquid-phase evaporation at the heap surface, while the

Table 1

Comparison of the model simulations conditions, grouped into the categories “controllable before stacking” and “controllable during leaching”, for both the “base” and “test” cases

Parameters		Base simulation	Other simulations
Controllable before stacking	Height	6 m	3 m 9 m 12 m
	Pyrite grade	2.5%	7% 15%
	Particle size (kinetics)	$2 \times 10^{-4} \text{ h}^{-1}$	$2 \times 10^{-2} \text{ h}^{-1}$ $2 \times 10^{-5} \text{ h}^{-1}$ $2 \times 10^{-6} \text{ h}^{-1}$
	Microbial pre-inoculation	None	Meso Meso/Mode Meso/Extr Meso/Mode/Extr
Controllable during leaching	Aeration rate	1.5 Nm ³ /m ² /h	0.3 Nm ³ /m ² /h 2.75 Nm ³ /m ² /h 4.0 Nm ³ /m ² /h
	Irrigation rate	5 L/m ² /h	2.5 L/m ² /h 10 L/m ² /h 15 L/m ² /h
	Drip spacing	25 cm	15 cm 35 cm 45 cm
	Inoculation	Meso/Mode/Extr	Meso Meso/Mode Meso/Extr None

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