

## OPTIMISING THE OPERATION OF BIOHEAPS

Paul L. Brown<sup>1</sup>, A. Ian M. Ritchie<sup>2</sup> and John W. Bennett<sup>1</sup>

<sup>1</sup> Sulfide Solutions Research, ANSTO, PMB 1, Menai, NSW 2234, Australia, [Paul.Brown@ansto.gov.au](mailto:Paul.Brown@ansto.gov.au)

<sup>2</sup> Ian Ritchie Consulting, Aldgate SA 5154, Australia, [goodrich@iweb.net.au](mailto:goodrich@iweb.net.au)

### ABSTRACT

Worldwide there is increasing interest in the use of biooxidation heaps to pre-treat refractory gold ores and bioleaching for metal extraction. The method offers a means of increasing metal recovery and lowering production costs. In addition, removing sulfides from a heap provides an environmental benefit when it comes to dealing with the spent material at the end of operation. Significant advances have been made in recent years in understanding the physical and chemical processes that govern the performance of bioheaps. In this paper, a conceptual model is presented that can be applied in the optimisation of the design and operation of bioheaps. Important parameters include heap geometry, intrinsic oxidation rate of the material, gas permeability, airflow rate, oxygen concentration distribution, temperature distribution, solution flow rate and pore water chemistry. In-situ instrumentation to monitor parameters within heaps during operation to ensure that conditions remain optimal will also be described. A computational tool that can be used to design and manage bioheaps will be discussed.

### INTRODUCTION

The terms bioleaching and biooxidation are often used interchangeably, however, there are distinct technical differences between the process technologies [Brierley, 1997]. Bioleaching refers to the use of bacteria (*Thiobacillus ferrooxidans* and thermophilic species) to leach a metal of value such as copper, zinc, uranium, nickel and cobalt from a sulfide mineral, and places the metal of interest in the solution phase during oxidation. The process is aimed at maximising metal recovery and the solid residue is discarded. Biooxidation refers to a pre-treatment process that uses the same bacteria to catalyse the degradation of mineral sulfides, usually pyrite or arsenopyrite, which host or occlude gold and/or silver [Brierley, 1997]. In contrast to bioleaching, the metal value remains in the solid phase and the solution is discarded. We will use the

term bioheap to refer to both biooxidation and bioleach heaps where properties or processes apply to both.

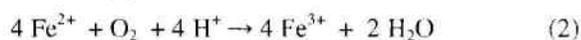
The economics of biooxidation require that typically about half of the sulfide sulfur present in the heap must be oxidised within about six months [Ritchie, 1997]. Commercial heaps are likely to contain a million tonnes or more of ore and, as such, need to be as high as possible to avoid profligate use of land area. This places constraints on the properties required of the heap material, the conditions within the heap and on the heap's operation in achieving the desired sulfide sulfur reduction. Similarly, in bioleach heaps physicochemical parameters are critically important in optimising leaching rates and recoveries. An understanding of the importance of the interaction of the physicochemical parameters involved in these processes can be obtained from the application of numerical models describing the processes, and subsequently, by monitoring the parameters during heap operation. The purpose of this paper is to describe a conceptual model that provides insights into the optimisation of operational parameters in bioheaps, to propose a number of monitoring techniques that provide feedback on heap performance, and present a computational tool that can be used to design and manage bioheaps.

### CONCEPTUAL MODEL OF BIOMINING HEAPS

The primary process that is central to biooxidation operations is the oxidation of pyrite, which can be described by reaction (1)



This reaction is relatively fast in the presence of catalysing bacteria such as *Thiobacillus ferrooxidans* and releases 1410 kJ mol<sup>-1</sup> of heat. These bacteria catalyse the reoxidation of ferrous iron produced in the above reaction back to ferric iron, as described by reaction (2)



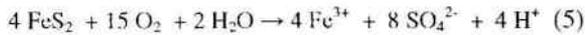
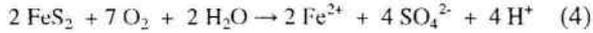
In bioleach heaps, the ferric iron is essential for the oxidation of metal sulfides present in the ore, such as the copper minerals covellite and chalcocite.

For bioheaps to be economically viable, the reactions described above need to proceed rapidly. A key measure is the timescale for oxidation of the sulfide sulfur. This can be derived from expression (3) [Ritchie, 1997]

$$t_s = \frac{P_s \omega_s^s}{S} \quad (3)$$

where  $t_s$  is the timescale for sulfide sulfur oxidation (in seconds),  $P_s$  is the bulk density of the heap (typically  $1500 \text{ kg m}^{-3}$ ),  $\omega_s^s$  is the mass fraction of sulfide sulfur within the heap (say 1%) and  $S$  is the sulfide sulfur oxidation rate. For  $t_s$  to be about six months, the oxidation rate,  $S$ , needs to be greater than  $5 \times 10^{-7} \text{ kg (S) m}^{-3} \text{ s}^{-1}$  and may be taken to be typically of the order of  $10^{-6} \text{ kg (S) m}^{-3} \text{ s}^{-1}$ .

Of importance in the sulfide sulfur oxidation process is the flux of oxygen into the system required to maintain oxidation throughout a heap at the required rate. Reactions (4) and (5) are derived from reactions (1) and (2) and can be used to quantify the amount of oxygen required in the overall oxidation process.



The flux of oxygen required to oxidise the sulfide sulfur at the required rate can be estimated from equation (6) which relates the gas specific discharge,  $q_g$ , to the properties of the heap, where the oxygen is completely consumed within the heap.

$$q_g = \frac{h \epsilon_o S}{P^g \omega^g o} \quad (6)$$

In the equation,  $h$  is the height of the heap,  $\epsilon_o$  is the ratio of the mass of oxygen used to the mass of sulfide sulfur oxidised,  $P^g$  is the intrinsic density of gas in the heap,  $\omega^g o$  is the mass fraction of oxygen in the gas phase. Using values typical of a heap, it can be shown [Ritchie, 1997] that a gas specific discharge of  $10^{-4} \text{ m s}^{-1}$  is required to oxidise the sulfide sulfur at the desired rate.

The gas specific discharge is related to other parameters by equation (7)

$$q_g = \frac{K}{\mu_g} \frac{\partial P}{\partial x} \quad (7)$$

where  $K$  is the gas permeability in the heap,  $\mu_g$  is the viscosity of the gas in the heap and  $\partial P/\partial x$  is the pressure gradient in the heap. It follows from equation (7) that for practical values of the applied pressure, the gas permeability  $K$  needs to be in the region  $10^{-11}$  to  $10^{-9} \text{ m}^2$  to achieve the required gas specific discharge rates.

As mentioned above, the oxidation reaction is exothermic producing a significant amount of heat. At the oxidation rate necessary to maintain an economic heap, the rate of heat production is high. Given that in practice a heap will generally have much larger lateral dimensions than the height, a heap can be reasonably considered to be one-dimensional from the point of view of heat transport. Under this assumption, the temperature rise within the heap above ambient,  $\Delta T$ , can be determined from expression (8) [Ritchie, 1994].

$$\Delta T = \frac{h^2 \delta S}{4 \kappa_{th}} \quad (8)$$

In the equation,  $\delta$  is the heat released per mass of sulfide sulfur oxidised,  $\kappa_{th}$  is the thermal conductivity of the heap and  $h$  and  $S$  are as previously defined. Using the typical parameter values mentioned earlier, it can be shown that a temperature rise well above  $100^\circ\text{C}$  can be produced. It is therefore evident that the heap must be cooled to maintain the heap in a temperature range where bacteria will be able to catalyse the oxidation. Two mechanisms are responsible for the removal of heat from a heap, thermal conduction and heat transport by fluid flow in both the pore water and gas [Ritchie, 1997].

From the above discussion, it is apparent that a number of physical factors are important in optimising the operation of a bioheap, including oxygen supply, temperature and irrigation rate. Similarly, a number of chemical factors will also be important including ferrous iron oxidation and secondary mineralisation which may affect the effectiveness of either the physical or chemical processes. Physical and chemical factors important for the optimisation of bioheaps will be discussed in the next section.

## FACTORS AFFECTING HEAP OPTIMISATION

### Physical factors

#### Oxygen supply

It is reasonable to expect that the oxygen concentration in the water within a heap, and thus available to oxidise the sulfide sulfur, is in equilibrium with the oxygen present in the pore space. This is

because water and gas transport rates within the heap are relatively low [Ritchie, 1997]. If the oxidation rate is proportional to the dissolved oxygen concentration then it must also be proportional to the pore gas oxygen concentration. Hammack and Watzlaf [1990] indicated that although the abiotic oxidation rate in small columns was proportional to the oxygen partial pressure in the pore space for partial pressures between 21 and 5%, for biotic systems the rate was almost constant down to a partial pressure of 1%, before it then decreased. The biotic oxidation is more appropriately described by Monod kinetics. By analogy, the relationship between the concentration of sulfide sulfur and the reaction rate is expected to exhibit the same Monod behaviour.

As was indicated above, to supply sufficient oxygen to maintain the sulfide sulfur at the required rate, it is necessary to sustain a high rate of gas specific discharge. As shown in equation (7), the main physical parameters that affect the gas discharge are the gas permeability and the forcing pressure of oxygen injection applied at the base of the heap. As an example, Ritchie [1997] demonstrated that a forcing pressure of 1000 Pa was sufficient to maintain a uniform oxygen concentration and sulfide sulfur oxidation rate throughout a 10 m heap having a gas permeability of  $10^{10} \text{ m}^2$ . Additionally, simulations performed with gas permeabilities of  $10^{11}$  and  $10^9 \text{ m}^2$  with forcing pressures of 10 000 and 100 Pa produced very similar results.

It is straightforward to instrument bioheaps with gas-sampling probes which enable the pore gas oxygen concentration distribution to be monitored. This information provides rapid feedback on the effectiveness of air blowers in supplying sufficient oxygen to all parts of the heap, to ensure that the overall sulfide sulfur oxidation rate is optimised. Such a monitoring system will show the effect on oxygen supply of any changes over time in gas permeability within the heap and allow appropriate adjustments to be made to operational parameters in a timely fashion.

### Temperature

The functional relationship between temperature and the sulfide sulfur oxidation rate in a bioheap can be considered as due to two processes. There is the process which depends on temperature through an activation energy and there is the bacterially catalysed component which depends on the temperature response of the microbial ecosystem.

The activation energy of pyrite in laboratory experiments under controlled conditions has been

studied by many workers. They have found a range of activation energies between 39 and 88  $\text{kJ mol}^{-1}$  [Lowson, 1982]. However, within a heap it is doubtful whether the activation energy is this large; field measurements in a waste rock dump by Bennett et al. (1993) over a temperature range of 0-10°C produced an activation energy of 10  $\text{kJ/mol}$ . The lower the activation energy the lower will be the increase in reaction rate as the temperature increases within the heap.

In considering the microbial ecology of a heap, it is recognised that bacterial populations have optimal activity at a particular temperature. At temperatures much above the optimum the bacteria lose their viability. For example, mesophilic and thermophilic bacteria catalyse the sulfide sulfur oxidation reaction at an optimum temperature of about 35 and 50°C, respectively. They lose their viability at about 40 and 55°C [Norris and Kelly, 1988]. As a consequence, it is necessary to hold the temperature of a heap within a narrow range for optimum oxidation. It is relatively straightforward to calculate the fluid flow rate required to maintain the temperature of the bulk of a heap within a given range.

Overall, the temperature dependence of the sulfide sulfur oxidation rate (using Monod kinetics),  $S$ , is given in equation (9).

$$S = \sigma_1 \frac{\omega_o^s}{\sigma_2 + \omega_o^s} \frac{\omega_s^s}{\sigma_3 + \omega_s^s} \alpha(T) \exp\left[\frac{-E_a}{R(T+273)}\right] \quad (9)$$

In the equation,  $\sigma_1$  is the oxidation rate at the maximum oxygen pore gas concentration and initial sulfide sulfur concentration,  $\sigma_2$  and  $\sigma_3$  are Monod kinetic parameters defining where the rate drops to half of its maximum rate,  $\omega_o^s$  and  $\omega_s^s$  are the mass fraction of oxygen in the gas phase and sulfide sulfur in the solid phase,  $T$  is the temperature in °C,  $\alpha(T)$  is a function relating to the microbial activity and is equal to unity up to some temperature,  $T_{\text{sick}}$  beyond which it decreases to zero at a temperature  $T_{\text{kill}}$ ,  $E_a$  is the activation energy and  $R$  is the universal gas constant. Similar equations can be constructed for the case where the oxidation rate varies linearly with the oxygen or sulfide sulfur mass fraction.

The temperature distribution within a heap can be monitored effectively using strings of thermistors. The strings can be laid during heap construction. The best placement of the thermistors can be determined from modelled predictions of heap performance. Information obtained during monitoring can be used to adjust irrigation rates to keep temperatures within the required range.

### *Irrigation rate*

As previously discussed, water passing through a heap has a significant bearing on the removal of heat, and therefore, is a critical parameter in optimising heap performance. If the water moves too slowly then the temperature within the heap may increase to the detriment of microbial viability. On the other hand, elevated irrigation rates may also result in less than optimal performance by reducing the pore space available for oxygen transport through the heap. This will reduce the gas permeability in the heap which, as can be seen from equation (7), will result in a decrease in the gas specific discharge, and hence, the flux of oxygen into the heap. The aim is to adjust the irrigation rate to optimise the balance between temperature control and oxygen transport.

### **Chemical factors**

#### *Ferrous iron oxidation and secondary mineralisation*

Bacterial oxidation of ferrous iron is a critical process in the bioleaching of pyrite, and further, is believed to be the rate controlling process in the bioleaching of all sulfide minerals [Boon et al., 1996] since ferric iron is the primary oxidant. The aim of aeration of the heap is to ensure regeneration of ferric ion throughout the heap and hence maintain a high sulfide sulfur oxidation rate throughout. Ferric ion can be introduced in the irrigation water but at the high oxidation rates required it is rapidly used up as it percolates through the heap. If the irrigation water is the only source of ferric ion a limit is put on the height of the heap.

The chemistry of iron in these systems is very complex involving the oxidative dissolution of sulfide minerals containing iron, such as pyrite, the bacterially catalysed oxidation of ferrous to ferric iron, the complexation of both ferrous and ferric iron, the formation of secondary iron precipitates and the adsorption of other components onto the surfaces of secondary iron minerals. The cycle, ferrous to ferric back to ferrous iron, occurs a number of times within the heap adding further complexity. Precipitation of ferricrete will reduce  $Fe^{3+}$  concentrations and will have the additional problem of reducing the permeability of the heap.

### **COMPUTATIONAL SIMULATION OF HEAP PERFORMANCE**

The conceptual model outlined above includes those physical, chemical and microbiological factors that are important in the optimisation of bioheaps. It is essential, however, that the complex interrelationship between each of the factors be considered simultaneously. This requires a sophisticated computational code, able to simulate conditions within the heap. Such a code helps identify which parameters and processes are important. It also clarifies those entities which should be monitored to ensure optimum heap performance.

The ANSTO code SULFIDOX is a two-dimensional finite difference code that describes a three-phase system consisting of a rigid solid porous phase through which gas and water phases flow. It models oxygen transport and depletion, heat transport and production, and reactant depletion in the solid phase. Thus, it models the oxidation of minerals, such as sulfidic material, and the dissolution of other mineral phases, such as carbonate and silicate minerals, present within the heap using chemical kinetics. Mass is transported in the aqueous phase and equilibrium is incorporated by the inclusion of a geochemical speciation model. This allows secondary mineralisation reactions to be considered. It also supports the inclusion of prescribed differential gas pressures (gas fluxes) at the base of the heap, thus permitting the simulation of the injection of air into the heap.

The application of SULFIDOX offers operators of bioheaps a practical tool that can be utilised at all stages of the bioheap life-cycle (from feasibility through planning and operation to closure), providing important information on the management and optimisation of bioheap performance.

### **REFERENCES**

- Bennett JW, AIM Ritchie, Y Tan (1993) A report to Boliden Mineral AB on the temperature dependence of pyritic oxidation rates in waste rock at the Aitik mine. ANSTO/C335.
- Brierley, C.L., 1997. Mining biotechnology: Research to commercial development and beyond. In: Biomining. Theory, Microbes and Industrial Processes, D.E. Rawlings (Ed.), Springer-Verlag, Berlin, pp. 3-17.

- Hammack, R.W. and Watzlaf, G.R., 1990. The effect of oxygen on pyrite oxidation. In: Proceedings of the mining and reclamation conference. Eds J. Skousen, J. Sencindiver and D. Samuel. West Virginia University, Morgantown, pp. 257-264.
- Lowson, R.T., 1982. Aqueous oxidation of pyrite by molecular oxygen. *Chemical Reviews*, **82**, 461-497.
- Norris, P.R. and Kelly, D.P., 1988. *Biohydrometallurgy*. Kew Science and Technology Letters.
- Ritchie, A.I.M., 1994. Sulfide oxidation mechanisms: controls and rates of oxygen transport. In: *Environmental geochemistry of mine-wastes*. MAC course handbook No. 22, D.W. Blowes and J.L. Jambor (Eds), Mineralogical Association of Canada, pp. 201-245.
- Ritchie, A.I.M., 1997. Optimization of biooxidation heaps. In: *Biomining. Theory, Microbes and Industrial Processes*, D.E. Rawlings (Ed.), Springer-Verlag, Berlin, pp. 201-226.