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Thermophilic heap leaching of a chalcopyrite concentrate [☆]

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Abstract

Thermophiles have been shown to be the only micro-organisms to leach chalcopyrite successfully. Heap leaching may be a feasible alternative to conventional bio-reactors, providing a high temperature environment can be maintained within the heap without external heating.

In the present study thermophilic heap leaching of a chalcopyrite concentrate coated onto inert support rocks (the GEOCOAT™ process) was studied in sets of small heated columns. The temperature was gradually increased to 70 °C, while successively introducing various mesophile and thermophile cultures. Individual columns were dismantled after progressively longer leach periods and the residual concentrates analysed. Copper extractions in excess of 90% were achieved within 100 days.

On the basis of head and residue analyses the rate of reaction heat generated was calculated. A comprehensive heap heat conservation model was used to determine whether the experimental temperatures can be achieved and maintained in a full scale heap. Results indicate that operating hot heaps successfully is possible within a certain range of process parameters.

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1. Introduction

Bio-leaching of sulphide minerals has become fairly well established technology and is widely applied in base metal extraction and pre-treatment of refractory gold ores (Brierley and Brierley, 1999). Technologies involve either leaching of mineral concentrate in various bio-reactor set-ups, or heap leaching of crushed and sometimes agglomerated whole ores. Most processes involve the use of mesophiles of the types *Thiobacillus* and *Leptospirillum* in the range 20–45 °C. The bacteria primarily facilitate the oxidation of ferrous to ferric by oxygen at or near the mineral surface, whereas the mineral is oxidised chemically by the ferric ions.

Chalcopyrite is the only sulphide mineral that does not respond well to mesophiles (Mehta and Murr, 1982), primarily because of its tendency to “passivate” at the high solution potentials (>600 mV vs. Ag/AgCl—Hackl et al., 1995; Kametami and Aoki, 1985) that are commonly associated with mesophile leaching, although the exact nature of this passivation is still the subject of

much debate (Kametami and Aoki, 1985; Dutrizac, 1989; Stott et al., 2000). However, thermophile micro-organisms, such as *Sulfolobus*, *Acidianus* and *Metallosphaera* have been shown to leach chalcopyrite to high extractions at temperatures in the range 65–75 °C (Konishi et al., 1999; Torres et al., 1995; Howard and Crundwell, 1999), both in shake flasks and stirred tanks. The success of thermophiles over mesophiles has not yet been clearly explained, but it has been observed that thermophile leaching takes place in a fairly low potential environment (380–500 mV Ag/AgCl) in which chalcopyrite passivation is not observed (Petersen et al., 2001; Gerike et al., 2001; Third et al., 2000). Reported rates of thermophile chalcopyrite leaching are generally significantly slower than those associated with mesophile bio-leaching at comparable conditions, which would be in line with the much lower potentials.

Commercial application of thermophile bio-leaching is under investigation (Gerike et al., 2001; d’Hugues et al., 2001; Miller, 1997), but the applicability of conventional bio-leach reactors may potentially be limited by a number of factors, such as an increased sensitivity of thermophiles to mechanical strain at high pulp densities (Clark and Norris, 1996; Nemati and Harrison, 1999), relatively long overall residence times (5–12 days) and hence the requirement of large reactor volumes.

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Thermophile bio-heap leaching, on the other hand, may be a feasible low-cost, low maintenance alternative, providing that the necessary temperature conditions for thermophiles can be achieved and maintained within the heap. Dixon (2000) has shown with the aid of a heap heat conservation model that it is possible to harness the heat of reaction in a sulphide heap to achieve optimal temperature distributions within.

Conventional heap leach operations may suffer from the fact that they usually involve very low grade ores, resulting in low mineral concentration per unit volume heap and hence low heat generation rates. Poor solution and air distribution within the heap as well as mineral occlusion in larger particles may further inhibit effective heat generation. The GEOCOAT™ process developed by GeoBiotics LLC involves spray-coating a ground mineral concentrate onto relatively coarse inert or low grade rock and then bio-heap leaching this coated material (Johansson et al., 1999). This aims to utilize the advantages of heap leaching (low capital and operating costs) while avoiding its draw-backs (long leach times, mineral occlusion). The GEOCOAT™ process may therefore also be advantageous in terms of operating a thermophile chalcopyrite heap leach.

This paper reports on the results from a number of mini-column tests conducted for different lengths of time on a GEOCOAT-ed chalcopyrite concentrate. Analysis of the residual concentrate allowed determination of the heat generation behaviour of this material. This data was then used in the Dixon heap heat conservation model to generate temperature profiles for full-scale GEOCOAT™ heap leach scenarios.

2. Experimental

2.1. Materials and micro-organisms

All tests were conducted with a chalcopyrite concentrate obtained from an operation in Northwestern Queensland, Australia. The concentrate had a head grade of approximately 75% chalcopyrite and 7% pyrite. Total copper, iron and sulphide sulphur grades were 26.8%, 27.5% and 28.8% respectively. The material was ground to 80% passing 40 μm with a mean particle diameter of 15 μm . For the support rock, granite pebbles in the size range 5–10 mm were used. The pebbles were soaked in 1 M sulphuric acid overnight and washed in distilled water prior to each test.

For forming the GEOCOAT, each kg of dry ground concentrate was slurried with 600 g distilled water to form a thick sludge, which was subsequently poured over the dried support rock in a bucket and tumbled to form an even coating. The coating density achieved was approximately 115 g concentrate per kg support (i.e. about 10% overall).

Micro-organisms used in the column experiments belonged to three different consortia:

- *Mesophiles*: containing strains of *Leptospirillum*, *Thiobacillus ferrooxidans* and *thiooxidans*, cultured at 30 °C.
- *Moderate thermophiles*: containing strains of *Sulfolobus*, *Acidianus* and *Sulfobacillus*, cultured at 48 °C.
- *Extreme thermophiles*: containing strains of *Acidianus*, *Metallosphaera* and *Sulfolobus*, cultured at 68 °C.

All consortia were adapted to the test concentrate in the course of 3–5 weeks prior to their use in the column experiments. All culturing was done in 100 ml shake flasks using standard growth media, with weekly transfers at 3:1 fresh nutrient solution to old medium.

2.2. Apparatus and procedure

The column leach experiments were conducted in 8 mini columns, 10 cm in diameter and 50 cm high (see schematic in Fig. 1), which were immersed in a constant temperature water bath operated between 30 and 80 ± 1 °C. Each column was charged with 2.8 kg support rock coated with approximately 320 g concentrate to a bed height of 30 cm. Each charge was prepared individually to allow exact determination of the amount of concentrate placed in each column.

Solution was fed to the top of the column from a feed container by means of a peristaltic pump at a rate of approximately 5 l/m² h, and collected at the base into a separate container. Air, enriched with 1% CO₂, was blown into the base of the column at a rate of approximately 2 m³/m² h.

Collected solution was sampled twice weekly and then re-blended with the residual feed. Evaporation

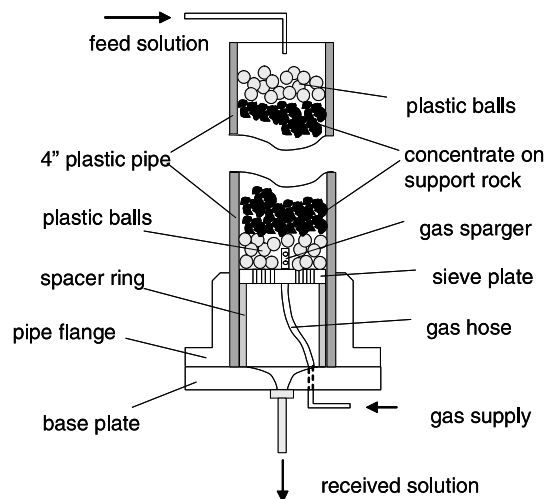


Fig. 1. Schematic drawing of the column leach apparatus.

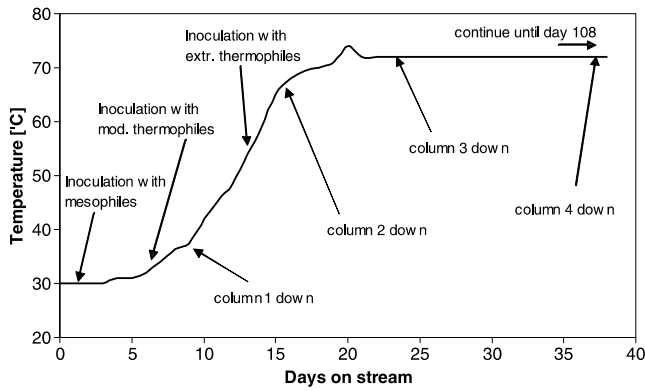


Fig. 2. Ramped temperature profile and schedule of operation.

losses were made up with distilled water to a total circulation volume of 4 l per column. The feed pH was adjusted to 1.3 with concentrated sulphuric acid. After 4 weeks on stream, 1 l of collected solution was discarded and replaced with distilled water every week in order to maintain dissolved copper levels below 6 g/l and iron concentrations around 4 g/l.

The columns were rinsed with acid for the first 2 days, and then inoculated with 100 ml of the consortium of mesophiles. The temperature in all experiments was raised from 30 °C at the beginning to 72 °C within 16 days. Fig. 2 indicates the temperature profile and the points at which the various consortia of micro-organisms were introduced into the columns. Columns C7 and C8, which were started later, were operated at 72 °C throughout and were inoculated with extreme thermophiles only. All columns were re-inoculated with a fresh charge of thermophiles every 2–3 weeks as a precaution.

Columns were dismantled after 1, 2, 3, 5, 6, 8, 13 and 15 weeks. The residual concentrate was recovered by washing the column charge repeatedly in mild sulphuric acid and removing the support pebbles with a sieve. The residual slurry was filtered, the recovered concentrate dried, weighed and analysed.

3. Results

Cu extraction from the individual columns was determined from solution assays, mass of concentrate filled and the initial head grade, as well as on the basis of assays of the residual solids (Fig. 3). In terms of Cu extraction the six initial columns started out all in more or less identical fashion, but leach curves began to diverge after day 16. Column C5 continued to leach at a more or less constant rate of about 0.85% per day, whereas columns C3 and C4 plateau-ed for 3 days before leaching continued at a slope similar to that observed in column C5.

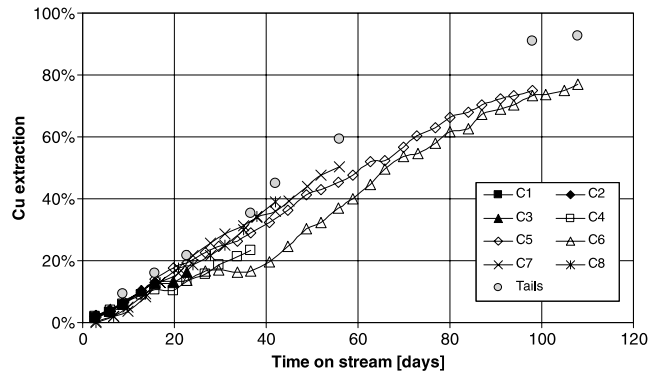


Fig. 3. Copper extraction in solution and based on tails assays.

Leaching in column C6 was initially erratic and appeared to have ceased altogether after day 25. It was found that the air supply lines to some of the columns had become clogged, reducing or completely cutting off the flow of air through the columns. This problem was later corrected and all columns resumed leaching after some delay. Interestingly, copper leaching in column C6 continued at a faster, but still linear rate (up to 1% per day) after the delay and eventually caught up with column C5.

Accounting for the stagnation periods during the run of column 6, a corrected leach profile, both in terms of solution and solids extraction, can be drawn (Fig. 4). Leach trends observed in all columns thus become almost identical, indicating generally good repeatability of the tests. The linear leach rate observed over most of the leach indicates that the reaction is reagent supply limited, very probably by the low solubility of atmospheric oxygen at high temperatures as well as the low rates of oxygen mass transfer in a heap scenario. Furthermore, it is interesting to note that both the longest running columns (C5 and C6) show a decline in the copper leaching rate only after day 78 at copper extractions exceeding 80%.

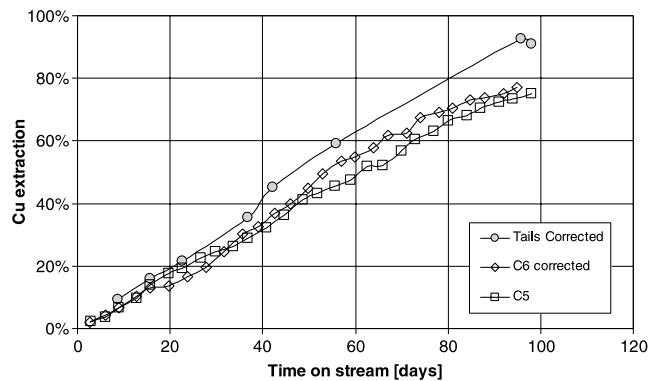


Fig. 4. Corrected copper leach profile for solution and solids extraction.

Copper extraction on the basis of assays of the recovered solids exceeds the solution assays initially by 3%, but the discrepancy becomes increasingly worse over the duration of the run, up to as much as 15% in columns C5 and C6. This is due to unaccounted copper in solution held up within the columns, washed out solids and cumulative error in the solution assays. The general trend, however, follows the solution extraction curves, indicating a more or less linear extraction profile until at least 80% extraction. A maximum copper extraction of 92.6% within 96 (active) days on stream was achieved in the present set of experiments.

Iron levels in the circulating solution built up to around 4 ± 0.5 g/l in all columns within the first 4 weeks and were kept at this level by regularly discarding a portion of the received solution. The extractions of iron, based on solids assays, are plotted in Fig. 5. These assays indicated increasing levels of residual sulphate with length of the run. Usually this is associated with precipitated jarosites of the form $XFe_3(SO_4)_2(OH)_6$ and thus seen as an indication that significant portions of oxidised iron may have remained in the solids as jarosites. Correcting overall iron extraction for this (assuming three irons for every two sulphates detected) indicates that iron extraction proceeded almost, but not quite, at the same rate as copper extraction (Fig. 5). Jarosite precipitation can account for as much as 15% of all oxidised iron. Chalcopyrite “passivation” has been attributed to jarosite precipitation at the mineral surface (Stott et al., 2000), and the decline of copper extraction

rates towards the end of the leach coincides with an increasing proportion of iron remaining in the solids as jarosite. However, as the gradual decline in copper leaching is marginal compared to the substantial precipitation of jarosite, it would appear that jarosite presents at worst a diffusion barrier rather than a passivating layer.

The oxidation of sulphide also proceeded at almost, but not quite, the rate of copper extraction (Fig. 5). Table 1 indicates the concentration of elemental sulphur per kg fresh concentrate in the course of the runs. It is interesting to note that sulphur oxidation initially yielded about half elemental sulphur, but later yielded almost entirely sulphate. This suggests that a certain concentration of elemental sulphur built up rapidly, but gradually disappeared again (Fig. 6). This observation could be indicative of a two-stage leach mechanism, whereby the sulphides are oxidised to elemental sulphur by one type of bacteria and the elemental sulphur to sulphate by another. The sulphur oxidisers would require some build-up of elemental sulphur before they could flourish and hence the second stage oxidation is somewhat delayed relative to the first.

The potential profiles are shown in Fig. 7. Columns C1–C6, which went through the heat-up phase, all showed a rapid rise of potential to very high levels associated with mesophile leaching of pyrite. Columns C1–C3 reached higher levels more rapidly than columns C4–C6, but all columns dropped back to potentials around 450 mV (vs. Ag/AgCl) at the end of the heat-up phase. At this stage only extreme thermophiles are likely

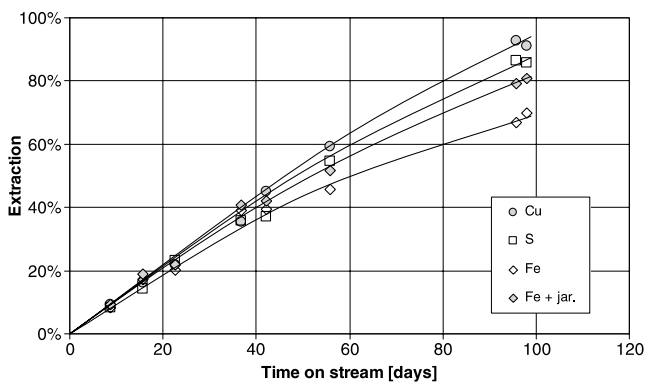


Fig. 5. Extraction based on tails assays for copper, sulphide sulphur and iron, as well as for iron corrected for the precipitation of jarosite.

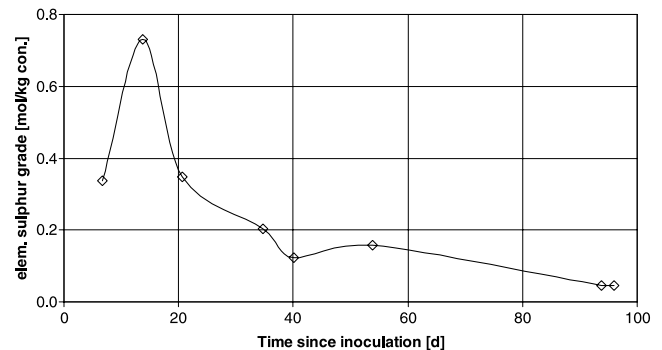


Fig. 6. Elemental sulphur concentration in the concentrate vs. time.

Table 1
Fate of sulphur species in the column runs

	C1	C2	C3	C4	C8	C7	C6 ^a	C5
Days since inoculation	6.7	13.68	20.69	34.68	40.11	53.9	93.81	95.92
% Sulphide oxidised	8.3	14.3	23.2	35.9	37.1	54.5	86.4	85.7
mol S ⁰ /kg concentration	0.338	0.732	0.348	0.204	0.123	0.159	0.045	0.046
% S ⁰ of total S oxidised	45	57	17	6	3	3	1	1

^a Corrected for stagnation periods.

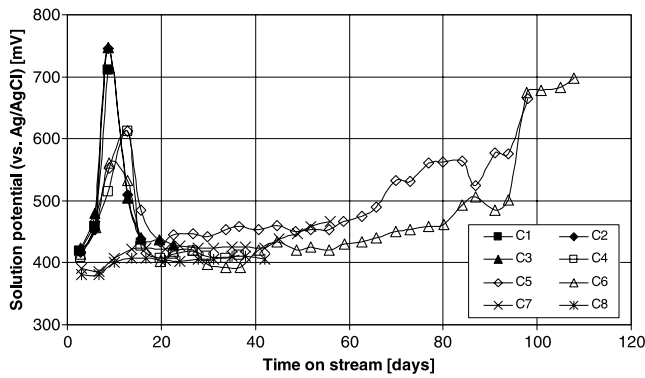


Fig. 7. Solution potential vs. time.

to have survived in the hot bed ($>60\text{ }^{\circ}\text{C}$). The later columns C7 and C8 remained at the low potential levels from the outset, as would be expected since these columns were never inoculated with mesophiles or moderate thermophiles. The temporary potential peak has not shown any effect on the rate of copper extraction and it appears that chalcopyrite “passivation” has not occurred (at least irreversibly) in the present tests, possibly due to the short duration of the high potential episode and an early introduction of thermophile micro-organisms (on day 7).

Potential levels remained in the 450 mV region until day 60, which corresponds to about 60% Cu extraction. Beyond this the potential began to rise slowly until it reached levels up to 700 mV. It is unclear at this stage what causes this potential rise, as chalcopyrite leach kinetics do not seem to be affected. It is interesting to note, that significant jarosite precipitation is also observed after day 60, which is in line with the higher prevalence of ferric ions at the higher potentials.

For columns C1–C6 pH levels rose from 1.3 to about 1.6 in each column pass during the first 20 days. This is related to the high rate of ferrous oxidation by mesophiles (and probably moderate thermophiles), which is acid consuming, while the corresponding sulphur oxidation to sulphuric acid is delayed until after the heat-up (see Fig. 6). The same effect was observed in the exclusively thermophile columns C7 and C8, but to a lesser degree. After day 20, pH levels in the solution received from all columns settled at approximately 1.3, indicating acid neutrality as would be expected from the overall process of chalcopyrite oxidation.

Bacterial counts on selected samples from the column effluents are shown in Fig. 8. The trend is relatively clear with counts rapidly reaching healthy numbers exceeding 5×10^7 cells/ml within the first 10 days of inoculation, but rapidly decreasing again to around 1×10^7 cells/ml over the following 10 days. Renewed increase to around 2×10^7 cells/ml is then noted up to day 40, followed by a very gradual, but continuous, decline for the remainder of the experiments. Visual observation reveals a gradual

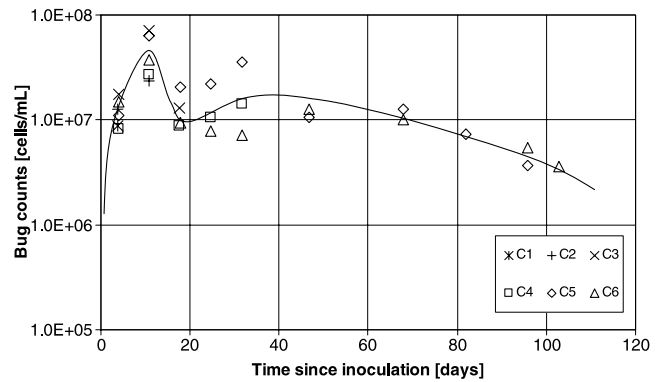


Fig. 8. Cell counts in the column effluent vs. time (the solid line indicates the general trend).

change from exclusively rod shaped bacteria before day 15 to exclusively spherical micro-organisms after day 30 in all column samples.

The initial peak is clearly related to the rapid growth of mesophilic and moderately thermophilic iron oxidisers promoting leaching primarily of pyrite at high solution potentials (see Fig. 7). The rod shaped bacteria observed are associated with the *Thiobacillus* type. After day 15 column temperature exceeds $60\text{ }^{\circ}\text{C}$, which results in the sudden drop in bacterial counts. Spherical thermophiles begin to emerge and rapidly replace any remaining rods. These thermophiles grow much more slowly than, and not as abundantly as, the mesophiles.

The gradual long-term decline in bacterial counts despite regular inoculations is probably related to the fact that, as leaching progresses, the mineral surfaces are not as accessible to the supply of oxygen, and hence bacterial growth (or maintenance) is restricted. This is partly supported by the declining rate of copper extraction after day 80 (Fig. 4) in the solution. Since no data point is available around day 80 it is unclear whether the extractions based on analysis of the solid residues also support this decline.

4. Heat generation modelling

The establishment of temperature profiles within a heap is governed by the interaction of heat generation within the heap through chemical reaction, heat transport down with the flowing solution, heat transport up with the upflow of humid air, boundary effects such as solar radiation and evapo-transpiration, and, to a lesser extent, by conduction through the rock. Dixon (2000) has formulated a comprehensive heap heat conservation model, which shows that the ratio of irrigation and aeration rates is critical in determining whether temperatures are high and well distributed over the height of the heap, or low and only mildly increasing towards the bottom. Thus, given values for the volumetric heat

generation rate for a specific mineral, the model can be used to predict temperature profiles within the heap and to obtain a range of operating parameters best suited to achieve and maintain any particular profile.

In the present case, the heat generation associated with the GEOCOAT-ed chalcopyrite concentrate can be established from a careful mass balance of copper, iron and sulphur species (sulphide, elemental sulphur, and sulphate) between initial charge and recovered residue assays for each column. This is translated into heat generation values by acknowledging that for any sulphide oxidation reaction involving molecular oxygen the heat of reaction generated is in the order of 100 kJ per mol electrons transferred, regardless of whether the

oxidation proceeds to elemental sulphur or to sulphate. This is indicated in Table 2.

The detailed heat analysis for the eight columns of the present study is reflected in Table 3. In order to obtain total heat generation, the moles of extracted sulphidic copper are multiplied by 200 kJ/mol, moles of extracted sulphidic iron by 300 kJ/mol (i.e. it is assumed all extracted iron is oxidised to ferric, which is reasonable given the near-steady-state levels of solution potential observed) and moles of sulphide oxidised to sulphate by 600 kJ/mol, whereas sulphide oxidised to elemental sulphur is ignored. This way the total amount of electrons transferred can be calculated without knowledge of the exact origin (pyrite or chalcopyrite) of the leached species.

The resulting heat generation data points are plotted in Fig. 9. The data suggest a more or less constant rate of heat generation after the initial start-up phase over the first 2 weeks. However, extrapolation of a linear trend beyond 54 days (C7) would suggest that heat

Table 2
Heats of reaction for some relevant sulphide oxidation reactions

Overall oxidation reaction	ΔH^0 (kJ/mol)
Oxidation of chalcopyrite to elemental sulphur (five electrons): $\text{CuFeS}_2 + 5/4\text{O}_2 + 5/2\text{H}_2\text{SO}_4 \rightarrow \text{CuSO}_4 + 1/2\text{Fe}_2(\text{SO}_4)_3 + 2\text{S}^0 + 5/2\text{H}_2\text{O}$	-508 (-102/e ⁻)
Oxidation of chalcopyrite to sulphate (17 electrons): $\text{CuFeS}_2 + 17/4\text{O}_2 + 1/2\text{H}_2\text{SO}_4 \rightarrow \text{CuSO}_4 + 1/2\text{Fe}_2(\text{SO}_4)_3 + 1/2\text{H}_2\text{O}$	-1755 (-103/e ⁻)
Oxidation of pyrite to elemental sulphur (three electrons): $\text{FeS}_2 + 3/4\text{O}_2 + 3/2\text{H}_2\text{SO}_4 \rightarrow 1/2\text{Fe}_2(\text{SO}_4)_3 + 2\text{S}^0 + 3/2\text{H}_2\text{O}$	-306 (-102/e ⁻)
Oxidation of pyrite to sulphate (15 electrons): $\text{FeS}_2 + 15/4\text{O}_2 + 1/2\text{H}_2\text{O} \rightarrow 1/2\text{Fe}_2(\text{SO}_4)_3 + 1/2\text{H}_2\text{SO}_4$	-1505 (-100/e ⁻)
Oxidation of elemental sulphur (six electrons): $\text{S}^0 + 3/2\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4$	-624 (-104/e ⁻)

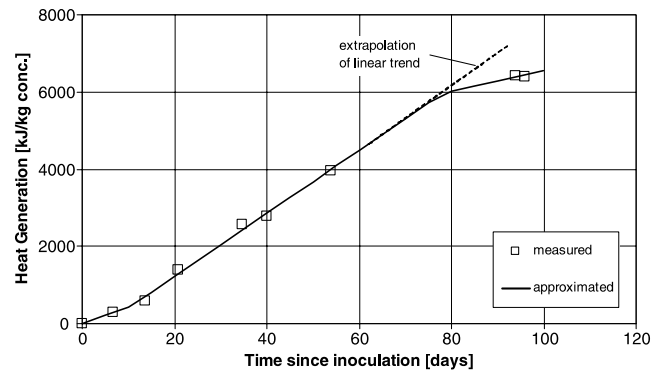


Fig. 9. Calculated heat generation data and the model approximation.

Table 3
Calculation of heat generation data for the experimental columns

	Head	C1	C2	C3	C4	C8	C7	C5	C6
Days leached		8.7	15.7	22.7	36.7	42.1	55.9	97.9	107.8
Days inoculated	0.0	6.7	13.7	20.7	34.7	40.1	53.9	95.9	93.8 ^a
<i>Extracted copper (mollkg)</i>									
Total	4.22	0.39	0.68	0.92	1.49	1.90	2.50	3.83	3.90
Sulphidic	3.98	0.16	0.44	0.68	1.26	1.66	2.26	3.60	3.67
<i>Extracted iron (mollkg) (including jarosite)</i>									
Total	4.92	0.46	0.92	1.07	2.01	2.07	2.54	3.97	3.90
Sulphidic	4.54	0.08	0.55	0.70	1.63	1.70	2.16	3.60	3.52
<i>Oxidised sulphur (mollkg)</i>									
Total	9.00	0.75	1.28	2.09	3.23	3.34	4.91	7.72	7.77
To SO		0.34	0.73	0.35	0.20	0.11	0.14	0.05	0.05
To SO ₄		0.41	0.55	1.74	3.03	3.23	4.77	7.67	7.73
<i>Heat generated (kJ/kg concentrate)</i>									
Total	0	303	583	1389	2559	2779	3963	6400	6427

^a Corrected for 10 days without gas supply.

generation in the last two columns (C5 and C6) must have fallen behind. It is therefore assumed here that the rate of heat generation dropped after day 78, which is in line with the observed decrease in copper extraction rate beyond this point (Fig. 4), increasing solution potential (Fig. 7) as well as dropping bacterial counts (Fig. 8). It is acknowledged that a data point based on assays of residual solids sampled around 78 days would have greatly helped to corroborate this assumption.

The time dependent heat generation $H(t)$ was thus approximated by a combination of three linear functions:

$$H(t) \text{ (kJ/kg)} = \begin{cases} 42.62t + 5.76 & 0 \leq t \leq 10.6 \text{ days} \\ 81.74t - 4.11 & 10.6 \leq t \leq 78.1 \text{ days} \\ 26.19t + 3927 & t \geq 78.1 \text{ days} \end{cases} \quad (1)$$

Similarly, the volumetric rate of heat generation $S(t)$ within a heap can be obtained by taking the derivative of Eq. (1) and multiplying by the effective in situ density of concentrate (here taken as 185 kg concentrate per m³ heap):

$$S(t) \text{ (W/m}^3\text{)} = \begin{cases} 91.27 & 0 \leq t \leq 10.6 \text{ days} \\ 175.0 & 10.6 \leq t \leq 78.1 \text{ days} \\ 56.07 & t \geq 78.1 \text{ days} \end{cases} \quad (2)$$

This function was entered into the Dixon heap heat conservation modelling code. Model parameters were set as indicated in Table 4, reflecting geo-climatic con-

Table 4
Heat model input parameters

Heap height (active)	$X = 5 \text{ m}$
Drainage layer height	$X_{\text{drain}} = 1 \text{ m}$
Average heap density	$\rho = 1700 \text{ kg/m}^3$
Average heap heat capacity	$C_p = 1000 \text{ J/kg K}$
Average heap thermal conductivity	$k = 1 \text{ W/m K}$
Initial heap temperature	$T_0 = 30 \text{ }^\circ\text{C}$
Solution heat capacity	$C_{\text{pl}} = 4184 \text{ J/kg K}$
Solution temperature	$T_1 = 25 \text{ }^\circ\text{C}$
Dry air heat capacity	$C_{\text{pa}} = 1000 \text{ J/kg K}$
Air temperature	$T_a = 30 \text{ }^\circ\text{C}$
Air relative humidity	$\omega_a = 50\%$
Latent heat of vapourization	$\lambda = 2360 \text{ kJ/kg}$
Water vapour heat capacity	$C_{\text{pv}} = 1840 \text{ J/kg K}$
Atmospheric pressure	$p = 0.967 \text{ atm}$
Minimum ambient temperature	$T_{\infty}^{\text{min}} = 20 \text{ }^\circ\text{C}$
Maximum ambient temperature	$T_{\infty}^{\text{max}} = 40 \text{ }^\circ\text{C}$
Ambient atmospheric relative humidity	$\omega_{\infty} = 50\%$
Surface heat transfer coefficient	$h = 20 \text{ W/m}^2 \text{ K}$
Water-vapour-in-air Lewis number	$Le_{\text{v-a}} = 1.25$
Heap surface solar absorptivity	$\alpha_s = 0.7$
Heap surface grey-body emissivity	$\epsilon = 0.9$
Heap-to-sky view factor	$F_{1-2} = 0.75$
Atmospheric attenuation factor	$t_a = 0.9$
Latitude	$l = -20.7^\circ$
Solar declination	$d = 0^\circ$ (equinox)
Minimum (night) sky temperature	$T_{\text{sky}}^{\text{min}} = -60 \text{ }^\circ\text{C}$
Maximum (noon) sky temperature	$T_{\text{sky}}^{\text{max}} = 40 \text{ }^\circ\text{C}$

ditions prevailing at the mine site in Northwestern Queensland. A base case heap height of 5 m plus a 1 m drainage layer were assumed. Fig. 10 shows the average heap temperature with time as a function of various irrigation and aeration rates with other parameters unchanged.

Most of these curves fall in the range 65–75 °C steady-state average temperature, which is desirable for effective thermophile leaching, and vary only marginally in the rate at which steady state is reached. A typical development of temperature profiles over the depth of the heap is shown in Fig. 11 for 8 l/m² h irrigation and 3 kg/m² h aeration rates. As can be seen, the heap heats up more or less homogeneously within the active zone, except near the top where environmental effects filter down. A temperature peak eventually develops near the top, which should be no more than 80 °C to avoid killing bacteria. Substantial cooling takes place only in the drainage layer, with the outflowing solution more or less at the same temperature as the inflowing. Most of the heat generated within the active zone is therefore

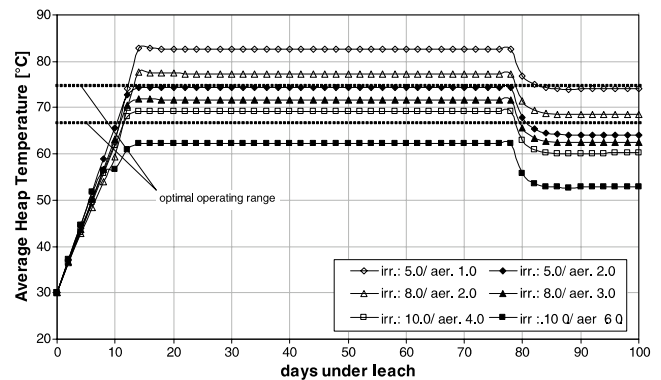


Fig. 10. Average heap temperature vs. time modelled for a variety of irrigation rates (in l/m² h) and aeration rates (in kg/m² h).

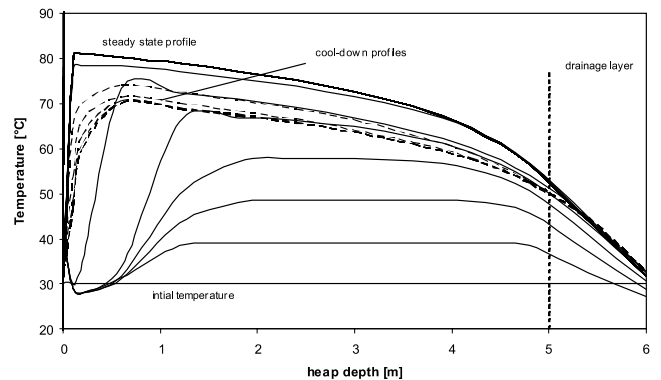


Fig. 11. Development of temperature profiles with heap depth at 8.0 l/m² h irrigation rate and 3.0 kg/m² h aeration rate (each line represents a progression of 2 days, dotted lines indicate cool-down profiles after day 78).

carried from the heap through the water vapour leaving at the top, and the rate of aeration can effectively be used to control the rate of cooling and hence steady-state temperatures. High rates of irrigation require high rates of aeration in order to remain in the target region. It should be noted that optimal irrigation rates (5–8 l/m² h) are lower than those applied in many industrial operations (10–20 l/m² h), whereas optimal aeration rates (2–3 kg/m² h) are considerably higher than typical industrial rates (<1 kg/m² h).

In the present scenario average heap temperatures drop quite suddenly after day 78, beyond which a lower heat generation rate applies (Eq. (1)). A new steady-state temperature is reached within a few days. This scenario is somewhat unrealistic as heat generation would probably level out gradually as the leachable portion of mineral diminishes, and heap temperatures would probably decrease continuously. Nevertheless, it is interesting to note that a more than threefold decrease in heat generation rate would result in a steady-state average temperature drop of only about 9 °C. Such a small drop could be counteracted by decreasing the aeration rate towards the end of the leach, thus ensuring that conditions for thermophile leaching prevail as long as possible to achieve maximum extraction.

Further modelling runs were conducted to test the effect of heap height (3.5, 5 and 6.5 m active zone with 1 m drainage layer) on the steady-state temperature profiles (before day 78) using a typical operating scenario with 8.0 l/m² h irrigation and 3.0 kg/m² h aeration. As shown in Fig. 12, the effect of heap height is relatively mild, but taller heaps under given conditions tend to retain too much heat with temperatures exceeding 80 °C in a substantial portion of the bed, whereas shorter heaps lose heat more easily and are slightly cooler on average. In the present scenario with its relatively high heat generation rates this might be in fact desirable, since temperature control with irrigation and aeration rates is relatively ineffective in taller heaps.

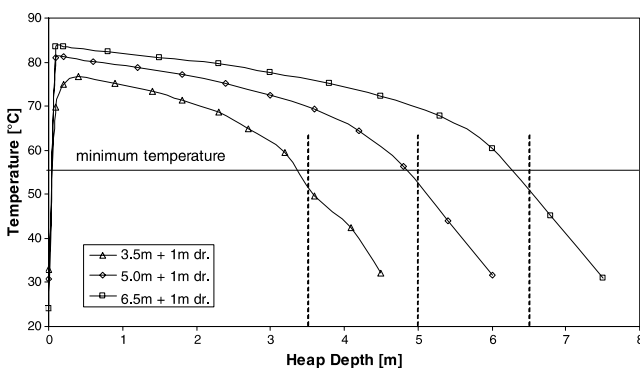


Fig. 12. Steady-state (day 50) temperature profiles with depth for different heap heights.

5. Conclusions

Chalcopyrite GEOCOAT™ leaching of a copper concentrate tested under conditions conducive to the growth of extreme thermophiles proceeded at a more or less linear rate of about 0.85–1% per day and achieved copper extractions exceeding 95% in 100 days. Leaching proceeded at low solution potentials (≈ 450 mV vs. Ag/AgCl), which increased only very gradually at high copper extractions. Iron leached at rates similar to copper, and substantial jarosite precipitation occurred in the later stages of the leach. Sulphide was oxidised preferentially to elemental sulphur initially, but almost exclusively to sulphate in later stages of the leach. The elemental sulphur built up initially gradually decreased, probably due to the delayed onset of sulphur-oxidising microbial activity. Cell counts showed initial rapid growth of rod shaped bacilli, which were gradually replaced by spherical thermophiles as temperatures exceeded 60 °C.

To achieve thermophilic bio-leaching conditions in a heap leach scenario, the heap first needs to heat-up via leaching in the temperature ranges of mesophiles and moderate thermophiles. The heat analysis presented here shows that this heating up is feasible in principle. Mesophiles and moderate thermophiles leach pyrite, but not chalcopyrite, at high potentials (600–700 mV vs. Ag/AgCl). While this provides the heat generation needed for heat-up, the presence of sufficient quantities of pyrite in the mineral (in the order of 5%) is essential. Chalcopyrite leaching commences upon the introduction of extreme thermophiles and solution potentials rapidly drop once temperatures exceed 60 °C, beyond which the rapid iron oxidising bacteria no longer survive. The linear rate of leaching observed from this point is probably limited by the low solubility of oxygen at the prevailing temperatures.

Assuming that heat generation data established from small column experiments can be scaled up, model predictions suggest that a full-scale GEOCOAT™ operation will easily achieve average temperatures in the 65–75 °C range within 2 weeks and maintain these temperatures for most of the leach. Some degree of temperature control can be achieved by varying heap irrigation and aeration rates. Different heap heights were also modelled indicating that shorter heaps (3.5 m active zone) allow somewhat more favourable temperature distributions than taller heaps, but are otherwise equivalent.

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