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Effect of Surface Area, Growth Media and Inert Solids on Bioleaching of Complex Zinc/Lead Sulphides

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ABSTRACT: The effects of surface area (as a function of particle size and pulp density), growth media and inert solids on the extraction of zinc from the complex sulphide ore/concentrate were evaluated using the mesophilic and moderately thermophilic bacteria. The results have shown that an increase in the available surface area via size reduction improves the dissolution of zinc from the ore at low pulp densities (1-2% w/v). However, excessive increase in the surface area with increasing pulp density was found to adversely influence the dissolution process due to the inability of the bacteria to maintain the oxidising conditions in favour of the mineral sought after. Addition of nutrient salts was found essential to sustain the optimum bioleaching activity and the concentration of nutrient salts to be provided appears to depend on the availability of substrate (i.e. head grade and/or pulp density) for bacterial oxidation. The addition of inert solids (quartz) was shown to have a limited effect on the bioleaching of the concentrate.

1 INTRODUCTION

Complex sulphide ores are difficult to treat by conventional extraction processes mainly due to the extremely fine dissemination of valuable sulphides and their intimate association with gangue minerals in the ore matrix (Barberly et al. 1980, Buchanan 1984, Logan et al. 1993). The beneficiation of complex sulphide ores containing zinc, lead and copper has traditionally used processes such as differential flotation to produce concentrates of sufficient grade to be treated for the recovery of contained values within a pyrometallurgical process route (Barbery et al. 1980, Chadwick 1996). However, the pyrometallurgical processes now endure stringent environmental regulations and high capital costs in addition to the low quality of end product with further refilling being often a necessity (Grant 1994, Gordon 1985)

Biooxidation of refractory gold concentrates have already proved an economically viable and competitive process with reduced environmental impact and low capital costs involved (Dew et al. 1997, Rawlings et al. 2003). This has led to the extension of the technology to the treatment of low grade and/or difficult-to-treat ores/concentrates in particular, for the recovery of copper, nickel, cobalt and zinc (Miller et al. 1999, Rawlings et al. 2003).

Bioleaching is inherently based on the use of acidophilic bacteria such as *T. ferrooxidans, L. ferrooxidans* (<40°C). *S. tlwrmosulftdooxidans* (45-55°C) and *S. metallic-its* (~70°C) that have the ability to oxidise inorganic substrates such as ferrous iron and/or elemental or reduced sulphur compounds (Norris et al. 2000. Suzuki 2001). The oxidation of ferrous iron (1) and elemental sulphur (2) leads to the formation of ferric iron and sulphuric acid respectively which act as lixiviant for the oxidative dissolution of sulphide minerals (MeS; Me: Metal e.g. Zn) (3) in acidic environments (Sand et al. 2001, Rawlings et al. 2003).

$$2Fe^{2+} + 1/2O_2 + 2H^+ \xrightarrow{bacteria} 2Fe^{3+} + H_2O \qquad (1)$$

$$S^0 + 3/2O_2 + H_2O \xrightarrow{bacteria} H_2SO_4 \qquad (2)$$

$$MeS + 2Fe^{3+} \rightarrow Me^{2+} + 2Fe^{2+} + S^0 \qquad (3)$$

Bioleaching of sulphide minerals is naturally a complex process with chemical and biological reactions occurring concomitantly. The acidophilic bacteria utilised as the mediator of the oxidative reactions (1&2) in bioleaching processes themselves establish the optimum conditions under which they optimally thrive. However, the optimum growth conditions may be adjusted in order to achieve the maximum rate and extraction of contained values (Bosecker 1997). This assumes the primary consideration is the overall chemical and microbiological aspects of the dissolution process.

The factors deemed of fundamental importance for a bioleaching process are temperature, acidity, metal toxicity, availability of oxygen and carbon dioxide, nutrients, and substrate (i.e. mineral surface area) (Bailey & Hansford 1993, Bosecker 1997). A culture medium is essentially a mixture of inorganic chemical compounds mainly to provide NH_4^+, $P0_4$'\ Mg^{2+}. K^+, Ca^{2+} and $S0_4^{:}$", which are utilised by bacteria for the synthesis of cellular material (Tuovinen & Bhatti 1999). Bacterial oxidation of sulphide minerals occurs through surface chemical reactions via the attachment of bacteria and/or the leaching by bacterially generated ferric iron and/or acid. The increased surface area through size reduction would be expected to lead to a high rate and extent of extraction at low pulp densities (Torma et al. 1970). However, there are certain practical limitations to increasing the pulp density due to the factors including the limitation of 0_2 and $C0_2$ transfer (Bailey & Hansford 1994, Boon "& Heijneri 1998), mechanical damage to bacteria (Deveci 2002), bacteria-to-solid ratio (Komnitsas & Pooley 1991) and the build-up of toxic products (Bailey & Hansford 1993).

In this study the effect of growth medium, particle size and pulp density, and inert solids on the bioleaching of a complex sulphide ore/concentrate was investigated using mesophilic and moderately thermophilic bacteria.

2 EXPERIMENTAL

2. / *Mineral Sample*

The ore and rougher concentrate samples were obtained respectively from the McArthur River and Elura deposits in Australia (Logan et al. 1993, Anon. 1983). The mineralogical analysis (XRD & SEM) revealed that sphalerite (ZnS), galena (PbS) and pyrite ($FeS_:$) occurred as the major sulphide phases and quartz ($SiO_:$) was the most abundant non-sulphide phase in the ore and concentrate matrix. The chemical composition of both samples is shown in Table 1. The crushed ore sample as received was dry-milled to d_{sl},=-250 urn or -85 urn prior to the experimental use while the concentrate sample was used as received (d_{so}=-28 urn).

Table I. Chemical composition of the ore and concentrate

Sample	% Zn	<•/< Fe	<7rPb	%S	Ag (K/ton)
Ore	162	7.95	5.60	15.2	59
Concentrate	45.4	8.95	2.94	29.1)	66

A number of size fractions (-250+125 pm, -125+90 urn, -90+63 pm, -63+45 um, -45+20 pm and -20 pm) were obtained from the ground ore *(ci_m=-250* pm) and used to study the particle size effect. High grade quartz material (-75 pm) was used as the inert solids to investigate the effect of solids on the activity of bacteria.

2.2 *Bac -teria and gro wth media*

DSM 583 *(T. feiTooxideins)* and the designated mixed cultures, mesophilic MES1 and moderately thermophilic MOT6 were used in this study. These cultures were grown and maintained on the ore (1-2% w/v) using orbital shakers at 30°C (DSM 583 and WJM) and 50°C (MOT6). An enriched salt solution with a composition of $MeS0_4$.7H^O (0.4 g/1). $(NH_4)_2S04$ (0.2 g/l), $K_2HPCC3H_:0$ (0".l g/1) and KCl (0.1 g/1) was used as the growth medium. Yeast extract (0.02% w/v) was provided for MOT6 culture to support the growth.

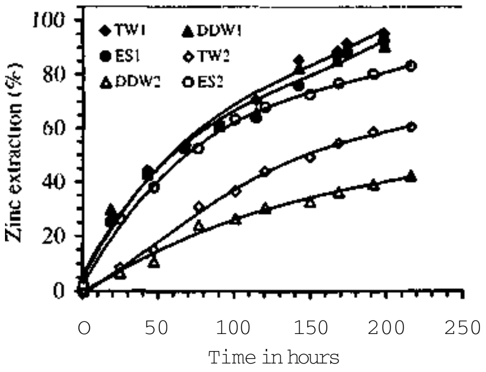
2.3 *Bioleaching experiments*

Bioleaching experiments were carried out in Erlenmeyer flasks (250 ml) containing 90 ml of enriched salt solution and 10 ml inoculum at the desired pulp density (% w/v). The progress of bioleaching and acid leaching (i.e. control) was followed by analysing the metal content (Zn and Fe) of the samples (1 ml) daily removed using an Atomic Absorption Spectrometer (AAS). pH and redox potential were also monitored and the pH was attempted to control if exceeded the initial pre-set values of 1.7 for the mesophilcs (DSM 583 and MES1) and 1.6 for the moderate thermophile MOT6.

3 RESULTS AND DISCUSSION

3.1 *Effect of growth medium on the bioleaching of the ore*

The effects of enriched salt solution (ES), double distilled water (DDW) and tap water (TW) as growth medium on the growth of DSM 583 strain are illustrated in Figure I. There was no significant difference in the rate and extent of metal dissolution in the first subculture (as denoted by "1") although a tendency for a decrease in the final extraction of zinc in DDW was noted. However, when the culture was subsequently subcultured onto fresh medium ("2") under the same conditions (i.e. ES->ES, TW->TW and DDW—»DDW) a remarkable deterioration in the dissolution of zinc became evident for the bacteria growing in DDW and TW as growth media. This limitation of the bacterial growth in DDW and TW appeared to be due to the limited availability of the nutrient components of enriched salt solution (ES).



hguie I Extraction of zinc tioni the oie by DSM 581 culture in the first (denoted by "I") and second ("2") subcultuies using enriched sali solution (ES), tap waiei (TW) and double distilled water (DDW) as the growth medium at 3()°C &
Ph I 7

The occurrence of comparably extensive growth (i.e. zinc dissolution) using these three media in the first subculture was most likely owing to the transfer of some salts with the initial inoculum (10% v/v), quantity of which (despite being >I0 times diluted) appeared adequate to support the build-up of biomass and hence to achieve significant dissolution of metals. More extensive extraction of zinc (60%) occurred in TW than in DDW (42%) in the second subculture was most likely due to the presence of anions and cations at relatively high concentrations in TW i.e. $Mg^{:+}$ (2.93 ppm cf. <<X001 ppm), $P0_4^{v}$ (0.31 cf. 0.15 ppm) and NO,' (5.4 cf. 0.1 ppm). These findings suggest that the requirement of growth media i.e. the concentrations of salts to be added would be determined by the quantity of the substrate available (i.e. head grade and/or pulp density) for bacterial oxidation.

Gomez et al. (1999) observed significantly higher extractions of metals (Zn, Cu and Fe) within 9K medium (no $Fe^{:+}$. $(NH_4)_2S0_4$, 3 s/1: $MgS0_4.7H,0$. 0.5 g/l; KH_2P0_4, 0.5 g/l: KCl. 0.1 g/l; CafNO^.HjO, 0.01 g/l) than those within the Norris medium (it has a similar composition to ES medium; the only difference being the concentration of $MgS0_4.7H_20$ (0.2 g/l compared with 0.4 g/l in ES). In light of the current findings the limitation of the extraction of metals in the Norris medium observed by Gomez et al. (1999) was probably due to the high metal content of the bulk concentrate i.e. 17.1 % Zn, 25.0% Fe and 14.0% Cu and operating pulp density (5% w/v) compared with the ore sample (Table I) (1% w/v) used in the current study. It was suggested that ammonium and phosphate are the most important nutrients for the bacteria with the deficiency of ammonium producing the most depressing effect (Morin et al. 1993,Tormaetal. 1970).

3.2 Effect of particle size on the hioleaching of the ore

An increase in the availability of the surface area via size reduction was observed to enhance the dissolution of zinc and iron. The extraction of zinc from the size fractions <-90+63 urn was in the range of 92-97% over the hioleaching period whilst only 77% of the zinc was solubilised from the coarsest fraction (-250+125 urn). Figure 2 illustrates the plot of the dissolution rate of zinc and iron versus the initial surface area per unit volume (the initial surface area was determined using nitrogen adsorption technique). A significant increase in the dissolution rate of zinc and iron was apparent as the surface area per unit volume increased from 26.7 m^2/I (-250+125 urn) to 33.1 nr/l (-63+45 um).

Torma et al. (1970) found a similar relationship between the metal extraction rate and particle size to that presented in Figure 2. However, Shrihari et al. (1991) observed an increase in the hioleaching rate of copper with increasing the particle size, which was attributed to the increased attachment efficiency of bacteria. Komnitsas & Pooley (1991) indicated that an excessive increase in the reactive surface area by either size reduction or increasing solids concentration per unit volume resulted in the inability of the bacterial culture to maintain high redox conditions i.e. high $Fe^{"+}/Fe^{:+}$ ratio to effectively drive the oxidation of pyrite, instead, having led to the enhancement in the selective oxidation of arsenopyrite over pyrite.

Figure 3 shows the positive influence of reducing particle size of the ore (2% w/v) from d_{X0}=-250 urn down to -85 urn on the dissolution of zinc using the mixed mesophilic MES1 and moderately thermophilic MOT6 cultures. The dissolution rate of zinc-by MOT6 and MES 1 cultures was found to increase

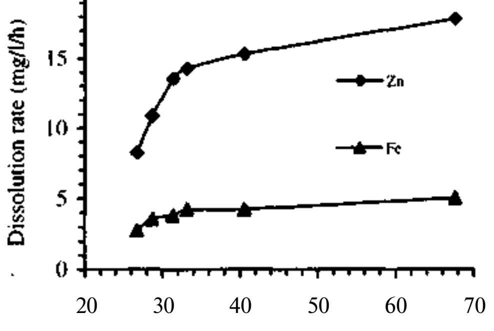
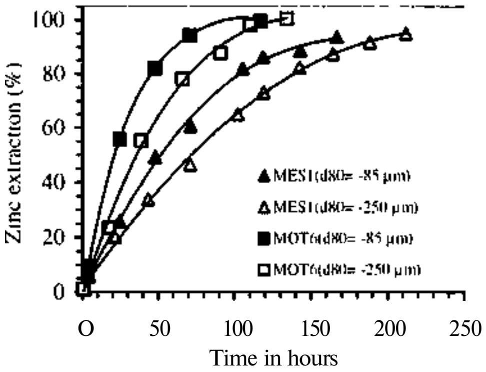


Figure 2. Effect of surface area as a function of particle size on the dissolution rate of zinc and iron from the oie (1%- w/v) using DSM 583 cultuie at 30°C



Figüre 3. Effect of reducing the particle size of the ore (2% w/v) on the extraction of zinc using MES1 (30°C & pH 1.7) and MOT6 (50°C & pH 1.6 & 0.02% w/v yeast extract)

by 40% and 29% respectively on decreasing the particle size of the ore with a considerable reduction in residence time. Consistently low redox potentials were recorded for the fine sample ($d_{8(1}$= -85 urn) e.g. 506 mV at 116 h compared with 631 mV even at 90 h for the coarse sample for MOT6 strain. This may indicate the relatively slow rate of accumulation of ternc iron generated by the strain in accordance with the increased surface area of the ore sample ($d_{s(}$>= -85 urn). In other words, the extraction of zinc from the coarse sample ($d_{8()}$= -250 pm) was "limited" by the available surface area allowing the accumulation of ferric iron at a faster rate.

The effect of decreasing particle size on the chemical (acid) leaching of the ore sample (in the absence of bacteria) was also evaluated as shown below in Figure 4.

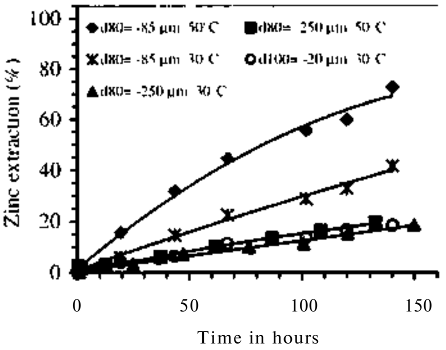


Figure 4. Effect of grinding on the acid leaching of zinc İroni the oie in the absence of bacteria at ^0^{U}C & 50'C

A remarkable enhancement in the chemical dissolution of zinc with decreasing the particle size of the ore sample from d_m= -250 urn to d_{xo}= -85 urn was noted to occur. However, the extraction of zinc from the -20 pm fraction, which had been obtained from the ore sample ($d_{s(}$)= -250 pm), was significantly lower than that from the d_{80}=-85 pm sample at 30°C (Fig. 4). The ore samples, $d_{,g,}$= -250 urn and d_5o= -85 pm had been prepared by tema-miliing the crushed ore as received for 10 sec and 30 sec respectively. There fore, the above findings suggest that the tema-milling for a longer period affected the leaching characteristic of the ore in such a way that led to the "activation" of the ore sample as this phenomenon had been reported by Balaz et al. (1994). They postulated that the grinding influenced the solid state properties of the sulphide phases inducing defects in the mineral structure and enhancing the anodic behaviour of sphalerite in mixture with pyrite.

3.3 Effect of pulp density on the bioleaching of ore using inesophilic bacteria at 30°C

Figures 5-6 illustrate the effect of pulp density (2-10% w/v) on the extraction of zinc and iron from the ore using MES1 culture. The dissolution rate (mg/i/h) of zinc was noted to increase with increasing pulp density from 2% w/v to 8% w/v, which was consistent with the increased availability of substrate (sphalerite). Notwithstanding this, the increase in the dissolution rate of zinc was not commensurate with the increase in the pulp density such that the rate increased 1.6 times despite a 2.5 times increase in the pulp density from 2 to 5%) w/v. The time required for >90% zinc extraction increased with pulp density in the range of 2-8%) w/v (Fig. 5). There appeared a "lag" period of 155 h prior to the acceleration of the extraction of zinc at 8% w/v. The release of zinc at 10% w/v though was only slightly better in the bioleaching experiment than that in the abiotic control experiment i.e. chemical leaching.

A significant increase in the dissolution rate of iron at 2-3% w/v (Fig. 6) appeared to coincide with 60-80% zinc extraction (Fig. 5) already occurred. However, the rate and extent of iron extraction (Fig. 6) declined with further increases in the pulp density (5-10% w/v). Despite the high zinc extractions (95-97%) there was no substantial increase in the dissolution of iron at 5-8%> w/v. In fact, a decrease in the concentration of iron at 8% w/v was observed during the final stages, which could be attributed to the precipitation of ferric iron.

The rate and extent of extraction of zinc and iron at 10%> w/v were low, only marginally better than the control (acid leaching) with the implication of a severely limited contribution of bacteria to the dissolution process, which was also consistent with the low redox potentials recorded (<404 mV) (Fig. 7). These low extractions at this pulp density may be attributed

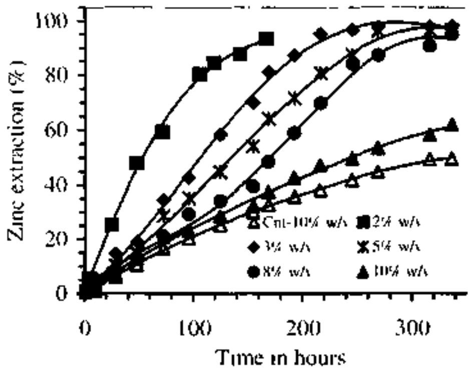


Figure 5 Effect of pulp density on the extraction of zinc from the ore ((^,.=-85 Mm) using MES I culture at 30°C & pH 1 7

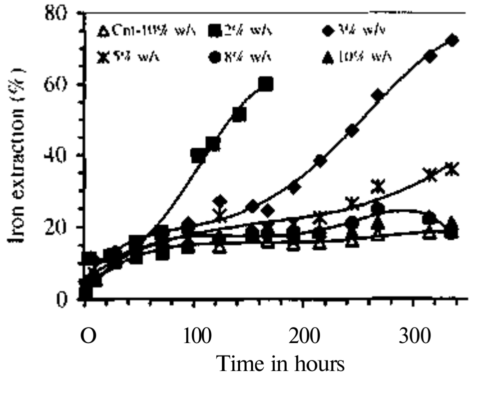


Figure 6 Effect of pulp density on the extraction of iron from the ore (d«n=-H5 pin) using MES1 culture at 30°C & pH 1.7

to a number of reasons. The increase in the residence time required for achieving the desired zinc-extractions (>90%) with increasing pulp density suggests that the bacteria-to-solid ratio at 10% w/v probably became too low to generate the ferric iron in sufficient quantity and hence to maintain the strong oxidising conditions. A similar (linear) pattern of zinc extraction observed at 8% and 10% w/v during the initial 155 h may well be interpreted as the implication of this phenomenon. Kommtsas & Pooley (1991) had also proposed that the number of free cells in suspension decreases at high pulp densities resulting in the low rate of production of ferric iron in solution compounded with the rapid consumption of ferric iron by the sulphides present due to high surface area per unit volume which would further aggravate the oxidising conditions.

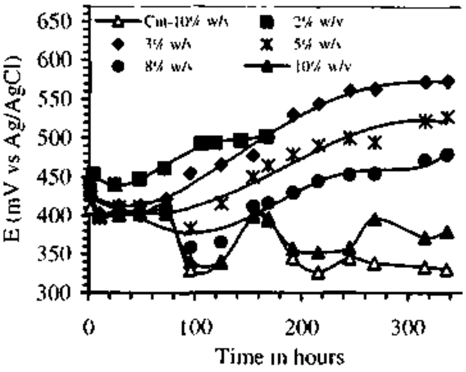


Figure 7. Redox potential profiles at different pulp densities during the bioleaching of the ore (d»n=-85 uni) using MES1 culture at 30°C & pH f 7

In addition to the low bacteria-to-solid ratio, as the pulp density increased, the concentration of metals in solution also increased e.g. 3.6 g/l zinc at 2% w/v compared with 13.1 g/l zinc at 8% w/v, which could have inhibited the growth and oxidising activity of bacteria. The culture MES1 was found to tolerate zinc concentrations of -10 g/l when grown on ferrous iron (100 mM) and at higher zinc concentrations the adaptation of the strain was necessary. It was also noted that the growth of the strain at high pulp densities (5-10%' w/v) improved, to some extent, with successive subculturing and gradually increasing the pulp density i.e. 5%-*8%->10%-M2% w/v. This improvement in the bioleaching of the ore may therefore be ascribed to the increase in the cell numbers (bacteria-to-solid ratio) within the inoculum as the pulp density incrementally increased and to the adaptation of bacteria to increasing concentrations of metal ions such as zinc.

The availability of oxygen and carbon dioxide dictates the oxidising activity of the bacteria and thus, the bioleaching rate of sulphide minerals would be controlled by the transfer rate of oxygen and carbon dioxide into the bioleaching media (Bailey & Hansford 1993, Boon & Hcijnen 1998). In this context, the time taken for achieving the same level of extraction would increase with increasing pulp density when the system operates under oxygen and carbon dioxide limited conditions, which is consistent with the current findings.

Following the termination of the experiments, the solid residues at 3-8% w/v were separated and examined by XRD. Consistent with the extensive dissolution of zinc obtained at 3-8%> w/v (Fig. 6) no sphalerite was detected. The XRD profiles also revealed that the galena present in the ore was extensively converted to lead-sulphate (anglesite) since no galena was found in the residues.

3.4 Effect of pulp density on the bioleaching of ore using moderately thermophilic bacteria at 50°C

The extraction of zinc and iron from the ore using MOT6 culture at different pulp densities is presented in Figures 8-9. A consistent delay prior to the onset of the substantial increase in the extraction of zinc occurred with increasing the pulp density from 2% to 8% w/v i.e. only 12% zinc extraction at 8% w/v compared with 51% zinc at *3%* w/v over an initial period ot 28 h. In contrast to the observed trend at <8% w/v, a linear trend similar to abiotic control (acid leaching) was observed at 10% w/v indicating the inability of the strain to efficiently drive the oxidation of the ore beyond the acid leaching.

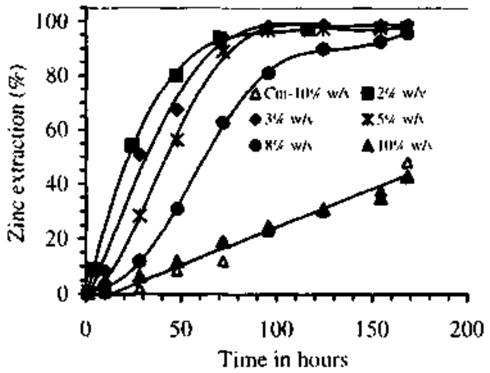


Figure S. Effect of pulp density on the extinction of zinc from the oie (d_s„=-X5 MITl) using MOT6 culture ;it 5()^{u}C & pH 1.6 & 0.02V; w/v yeast extract.

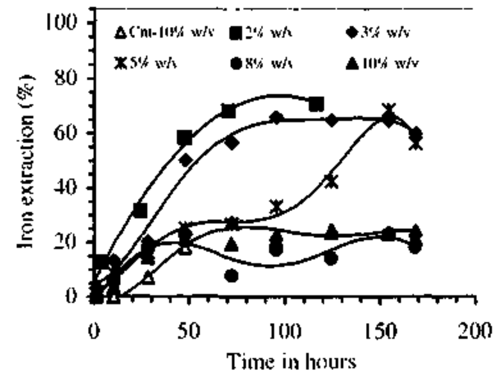


Figure 9. Effect of pulp density on the extraction ot zinc from the oie (d_w>=-85 urn) using MOT6 culture at 50°C & pH 1.6 & 0.02"/» w/v yeast extiact.

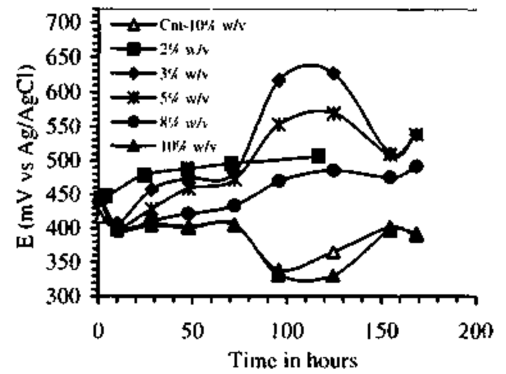
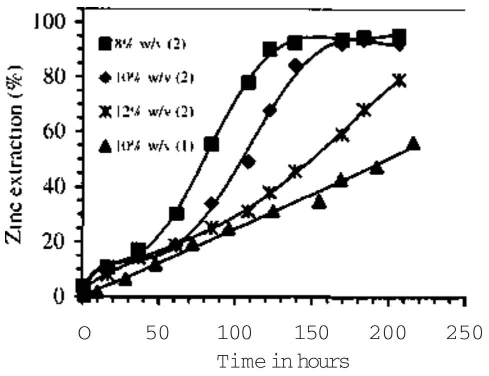


Figure 10. Redox potential profiles at different pulp densities during the bioleaching of the ore (d_sıı=-85 um) MOT6 culture at 50°C & pH 1.6 & 0.02% w/v yeast extract

The loss of some iron from solution occurred at 3-5% w/v following a bioleaching period of 155 h as shown in Figure 9. Similarly, the fluctuations observed in the extraction of iron at 8% w/v suggested the occurrence of the concurrent precipitation of ferric iron. These observations were consistent with the redox potential profiles produced at each pulp density (Fig. 10). The drop in the redox potential at 3-5% w/v after 124 h may indicate the decrease in the Fe'^/Fe^{2}* ratio probably in conjunction with the precipitation of ferric iron from solution.

The XRD analysis *of* the residues (at 3-8% w/v) revealed the presence of K-jarosite. The only difference in the XRD profiles produced at each pulp density was the absence of pyrite in the residues for 3% w/v, which suggested more extensive dissolution of iron than that observed (60%) in Figure 9. The implication is that the actual extraction of iron could have been masked by the precipitation of ferric iron during the dissolution process. The XRD profiles also affirmed the extensive oxidation of sphalerite and galena present in the ore sample.

After the experiments had been terminated, using the strain grown in the flasks at 8%> w/v as the inoculum, further tests were conducted at pulp densities 8% w/v to 12% w/v and the results were compared with the earlier tests as coded (Din Figure 11. A significant improvement in the extraction of zinc in the second subculture at 10% w/v was apparent (i.e. a 2.8-fold increase in the dissolution rate of zinc). Furthermore, an increase in the extraction of zinc even at 12% w/v was also observed during the later stages of the process (>139 h). This enhancement in the extraction of zinc in the second subculture at 10% w/v can be attributed to the utilisation of the inoculum grown at 8%> w/v at which the strain had been presumably adapted to the high concentrations



Figuie 11 Extinction of zinc fiom the oie (dsu=-8S pin) using MOT6 culture giown at 2% w/v (denoted us "I") and at 8% *w/v ("2")* as inoculum at 8-12% w/v & 50°C & pH 1 6 & 0 02% w/v yeast extiact

of zinc (-13 g/l) and/or the number bacteria was most likely high due to the increased availability of the substrate in comparison with the inoculum used in the first subculture, which had been grown at 2% w/v. These findings accord with the earlier presumptions as regards the adverse effect of low bactena-to-solid ratio and the inhibitory effect of increasing concentrations of metal ions at high pulp densities.

The moderate thermophile MOT6 appeared to sustain a better growth than the mesophile MES1 in response to the increase in pulp density. This could be attributed, in part, to the supplementary addition of 0.02% w/v yeast extract, which is utilised as a source of cellular carbon by moderate thermophiles. However, the mesophilıc MES1 culture is strictly autotrophic and requires atmospheric carbon dioxide to obtain their cellular carbon. Boon & Heijnen (1998) suggested that the decrease in the biooxidation kinetics at high pulp densities was, to a large extent, related to the exhaustion of carbon dioxide in the bioleaching medium. They also estimated that the amount of carbon dioxide available in a shake flask containing 100 ml slurry with I g/l pyrite would be consumed within 1 h.

3.5 Effect of (inert) solids on the bioleaching of i oncentrate

Tonna et al. (1970) had mooted that the decrease in the bioleaching rate at high pulp densities (>20% w/v) could have resulted from the destruction of bacteria by solids attrition. Dispinto et al. (1981) found that the addition of glass beads (0-5% w/v) led to the extension of initial lag period with no growth to occur at 5% w/v beads during the oxidation of ferrous iron by *T. fetroo.xidans* in shake flasks. Similarly, Curutchet et al. (1990) observed that the bioleaching rate of copper from covellite (0.01% w/v) decreased with increasing the amount of quartz added with a negligible growth at 8% w/v. They interpreted the adverse effect to the attachment of bacteria to quartz particles.

In this study, the addition of inert quartz particles was found to have no apparent effect on the leaching activity of MES I culture up to 13% w/v albeit an increase in the extent of lag period with increasing the concentration of quartz added from I to 8% w/v was observed for MOT6 culture (data not shown). These findings were consistent with the redox profiles (not shown) indicating the inability of MOT6 culture to maintain the oxidising conditions (>400 mV) required to efficiently drive the extraction of zinc over the lag periods observed. Presuming that the capacity of the system for the production of ferric iron would be directly proportional to the number of viable bacteria present, the low redox potentials can be attributed to the low bacterial numbers presumably due to the damage to bacterial cells by the action of solid particles at a particular pulp density.

Further tests using a stronger inoculum even at high concentrations of quartz (13-18% w/v) showed no adverse effect of quartz particles on the rate and extent of extraction of zinc as presented in Figure 12 where the pulp density of the concentrate was kept constant at 2% w/v. Consistently, the bacterial population was able to sustain high redox potentials (>431 mV) over the bioleaching period (Fig. 12).

The current and literature data suggest that solids could cause mechanical damage to the bacterial cells but providing the bacterial population could maintain sufficiently high oxidising conditions, no adverse effect on the metal extraction would probably be experienced.

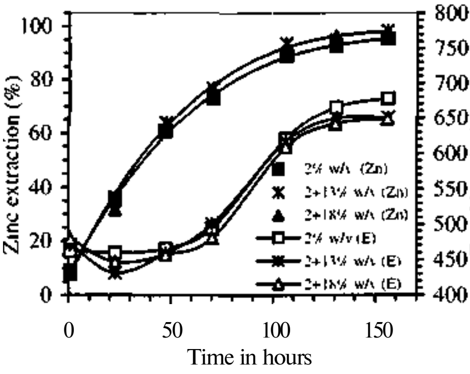


Figure 12. Exiiaction ot zinc fiom Ihe concentiate (2% w/v) and ledox profiles pioduced using MOT6 cultuie (50"C & pH I 6 & 0 02% w/v yeast extract) m the presence of 13-18% w/v quartz

4 CONCLUSIONS

This study has shown that the provision of nutrient salts in the growth medium is essential to sustain optimum bioleaching activity. Quantity of nutrient salts within the growth medium appears to depend on the head grade and/or the pulp density.

The increase in the available surface area via size reduction was found to enhance the dissolution of zinc from the ore at low pulp densities (1-2% w/v) and also the size reduction (i.e. grinding) may '"activate" the sulphide minerals. However, the excessive increase in the surface area with increasing pulp density was shown to adversely influence the dissolution process leading to a prolonged residence time lo achieve the desired zinc extraction. This was consistent with the inability of the bacterial cultures to maintain the oxidising conditions required for the efficient dissolution of zinc (>400 mV). The adverse effect of increasing pulp density can be attributed i) to the decrease in the number of bacteria-to-solid ratio, ii) to the inhibitory effect of increasing concentrations of metal ions in solution, iii) to the limited availability/transfer of oxygen and carbon dioxide (i.e. increasing demand for these gasses) with increasing pulp density, and iv) to the mechanical damage to the bacterial cells by solids.

The moderate thermophile M0T6 culture appeared to sustain a better growth than the mesophile MES1 in response to the increase in pulp density probably due to the supplementary addition of yeast extract (0.02% w/v) as a source of cellular carbon. The use ot strong inoculum i.e. prepared/grown at high pulp densities could, to some extent, alleviate the adverse effect of increasing pulp density probably due to a high cell-to-solid ratio within the system. The addition of inert solids even at high concentrations was found to produce a limited effect on the bioleaching process.

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