BIOLEACHING STRATEGIES FOR THE TREATMENT OF NICKEL-COPPER SULFIDE CONCENTRATES

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Different process options for the bioleaching of nickel-copper containing sulfide concentrates were evaluated. Tests in continuously operated systems showed >98% nickel extraction at temperatures ranging between 37 and 70°C, whereas for copper, occurring as chalcopyrite, extractions of >95 % could only be achieved at 70°C. Further optimisation of the process focused on determining the effects of process parameters such as temperature, grind size, residence time, redox control and feed solids concentration on the leach kinetics, metals extractions and performance of both moderate thermophile and thermophile cultures. Redox control in the first-stage reactor resulted in considerably faster copper leach rates and extractions of up to 95% could be achieved at increased feed concentrations and coarser grind sizes. High redox levels in the secondary reactors ensured >98% nickel recoveries. These operating conditions and control strategies have the potential to increase the rates of nickel and copper extractions to the extent that leaching times can be considerably reduced.

Keywords: Bioleaching, nickel, copper, moderate thermophiles, thermophiles, redox

1. INTRODUCTION

Copper-nickel ores are conventionally processed using selective flotation to produce separate concentrates, which are transported to copper and nickel refineries for smelting and refining. The need to produce an economically acceptable concentrate-grade for smelting often results in significant losses of metal values over flotation. An advantage of bioleaching processes is that lower grade bulk flotation concentrates can be treated, with the consequent advantage of achieving higher overall recoveries of metal values.

While the bioleaching of nickel and copper (especially chalcopyrite) concentrates using a variety of microbial cultures have been studied extensively, very little published data is available on the tank bioleaching of polymetallic nickel-copper concentrates (Morin et al., 2008). Studies have shown that sulfide concentrates containing nickel could be bioleached using mesophilic bacteria (Watling 2008), while limited data for bioleaching using thermophilic microbes are available (Dew *et al*., 2000). The presence of chalcopyrite in the polymetallic concentrates presents additional challenges, since it is not readily leachable at low operating temperatures and generally requires the use of operating temperatures ranging between 65 and 78°C (d'Hugues *et al*., 2002, Batty and Rorke 2006).

Low-grade nickel-containing sulfide ores are also suitable for heap bioleach applications and in recent years the technology has been applied on laboratory scale for the treatment of low-grade nickel sulfides (Zhen et al., 2008, Watling et al., 2009), black schist ore containing nickel as pentlandite and violarite (Puhakka *et al*., 2007) and has been successfully demonstrated at large scale at the Talvivaara Mine, located in Sotkamo, Finland (Riekkola-Vanhanen, 2010) and Radio Hill Mine, Western Australia (Watling 2008).

In this paper, bioleaching strategies for the treatment of a concentrate containing nickel as pentlandite and copper as chalcopyrite is discussed. The challenge was to develop a bioleaching process that maximized the extraction of both copper and nickel. The effects of process parameters such as temperature, grind size, residence time, redox control and feed solids concentration on the leach kinetics, metals extractions and performance of both moderate thermophile and thermophile cultures were investigated.

2. EXPERIMENTAL

2.1. Mineral characteristics

The test work was performed using Aguablanca, a low-grade Ni-Cu concentrate from Spain. The concentrate was fine-milled in a stirred ball mill to particle sizes varying between d_{90}=10 and 40µm. The chemical composition of the concentrate is presented in Table 1.

Table 1. Typical chemical analysis of the concentrate

Element	Mass (%)
Cu	7.2
Ni	5.6
Fe	32.7
S^{tot}	32.5
S^{2-}	32.2
S^0	0.1
Si	5.4

The different proportions of each mineral phase in the feed concentrate were determined by scanning electron microscopy (SEM) based image analysis. This analysis shows that the bulk of the concentrate comprised pyrite, pyrrhotite, chalcopyrite and pentlandite. Modal analysis of the feed is presented in Table 2.

Table 2. Modal composition of the concentrate based on SEM analysis

Mineral	Mass (%)
Chalcopyrite	18.5
Pentlandite	14.5
Pyrite	23.7
Pyrrhotite	20.7
Gersdorffite	0.04
Sphalerite	0.02
Galena	0.02
Cu-sulfides (mostly covellite)	0.03
Silicates	21.6
Oxides	0.6
Sulfates	0.4

2.2. Inoculum

The study was performed with moderate thermophile (45°C) and thermophile (70°C) cultures, which have been maintained at Mintek for several years. The moderate thermophile culture contained *Acidithiobacillus caldus*, *Leptospirillum ferriphilum*, *Sulfobacillus* sp. and *Ferroplasma* sp. (Okibe et al., 2003), while the thermophile culture was dominated by *Acidianus brierleyi*, with lower numbers of *Metallosphaera sedula* and *Sulfolobus* sp. present (Dinkla et al., 2009).

2.1. Ferric leach tests

Batch ferric leach tests were performed in fully baffled, mechanically agitated 6-litre reactors. A pulp density of 2% solids was used and the pH was controlled at a level of 1.4 with sulphuric acid. The tests were controlled at the set redox potential level by H_2O_2 addition. Cu and Ni extractions were followed by daily analysis of liquor samples using atomic absorption spectrophotometry.

2.2. Continuously operated reactors

The test work was performed in continuously operated reactors. Each system consisted of a feed pulp tank, single-stage, 3-stage or 4-stage reactors in series and a container at the end for product collection. The reactors were fully baffled and agitation was by means of a single 6-blade flat-blade Rushton turbine. The air supply was enriched with 0.3% CO_2 and supplied to the reactors by means of a sparger situated below the impeller.

Feed slurry was fed to the reactor from the feed tank via a peristaltic pump. Nutrients were added to the feed tank at the following concentrations: 1g/l $(NH_4)_2SO_4$, 0.5g/l $MgSO_4.7H_2O$, 0.1g/l KCl and 0.5g/l K_2HPO_4. Pulp was transferred between the reactors using the same peristaltic pump. The air flow rates were controlled by a rotameter and control of the operating temperature in the reactors was achieved using a temperature controller via temperature probes and immersion heaters. The impeller speed was set at 450 rpm, while operating at high redox potential levels. A controller was used to control the redox potential at low levels. The output from the controller adjusted the impeller speed to control the mass transfer supply of oxygen, thereby maintaining the redox potential at the set point.

The reactors were daily monitored for temperature, pH, redox potential and oxygen and carbon dioxide uptake rates. The levels of Fe, Ni and Cu in solution were measured daily by atomic absorption spectrophotometry. Once steady state conditions were reached, a set of pulp samples were collected from each reactor and the residues analysed for Fe, Cu, Ni, sulphide sulphur and elemental sulphur content.

3. RESULTS AND DISCUSSION

3.1. Bioleach amenability tests performed at 45 and 70°C

Bench-scale piloting facilities were assembled to allow open-circuit bioleaching of the Ni-Cu concentrate using the moderate thermophile and thermophile cultures. These facilities provided for close control and monitoring of the bioleaching process, allowing simulation of near-industrial scale conditions and control.

The test work was performed in 3-stage continuously operated reactors at 10% feed solids at a particle size of d_{90}=10µm and a 6-day overall residence time at 45 and 70°C respectively. No attempt was made to control the pH and pH levels between 1.3 and 1.5 were measured in all reactors. High redox potential levels (> 600mV, Ag|AgCl) were recorded in all stages.

The results showed that >98% Ni extraction could be obtained at 45 and 70^{o}C, but the leach kinetics was slower at the lower temperature (Figure 1). At 70°C, 95% Cu extraction was achieved, while chalcopyrite was only partially oxidised at 45°C and a final Cu extraction of 74% could be obtained (Figure 1). These results were not unexpected. Although it is known that nickel sulfide oxidation is moderately temperature dependent (Watling 2008, Cruz *et al.*, 2010), Ni can be successfully recovered at low to moderate operating temperatures (Dew et al., 2000). The passivation of chalcopyrite at low operating temperatures is a well-known phenomenon which has been addressed in numerous papers (Stott *et al.*, 2000; Parker *et al.*, 2003; Sandstrom *et al.*, 2005; Klauber 2008).

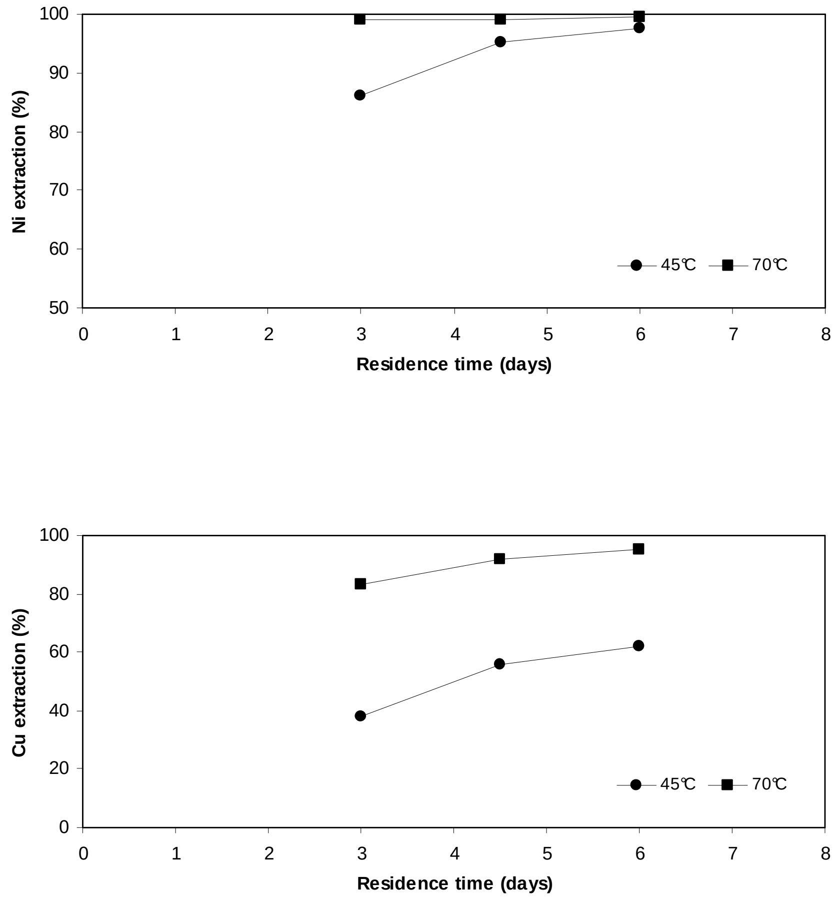

Figure 1. Ni and Cu extractions obtained at 45 and 70°C during bioleach amenability test work in 3-stage continuously operated reactor systems

3.2. Process optimisation

Further research was carried out to investigate additional avenues for process optimisation. Optimisation of the process focused on determining the effects of operating parameters such as temperature, grind size, residence time, redox control and feed solids concentration on the leach kinetics, metals extractions and performance of both moderate thermophile and thermophile cultures. The results obtained during the amenability test work were used as baseline data.

3.2.1. The effect of grind size on metal extractions using thermophiles

The need for ultra-fine milling of feed concentrates represents an additional process cost and could cause downstream complications for bioleach plants treating base metal concentrates. In general, it is found that the leach kinetics and metal extractions increase with decreasing grind size. However, it has also been shown that an optimum grind size exists with regard to the growth rates of the thermophile culture (Nemati *et al*., 2000). Further optimisation tests at 70°C therefore focused on determining the maximum grind size which could be used, while still achieving optimum leach kinetics and metal extractions. The tests included a series of ferric leach and bioleach tests at grind sizes ranging between 10 and 40 μm.

The results obtained from the ferric leach tests performed at 70 °C and 600 mV showed that ≥98% nickel extractions could be obtained over the range of grind sizes evaluated. There was, however, a reduction in copper extractions from 98% to 68% with increasing particle size (Table 3).

Table 3. The effect of grind size on Cu and Ni extractions as determined by ferric leach tests performed at 70°C

Grind size (d_{90}) (μm)	Cu extraction (%)	Ni extraction (%)
10	98	99
20	87	98
25	82	98
40	68	98

These results were confirmed by bioleach test work performed in continuously-operated reactors on concentrate milled to particle sizes of d_{90}=10, 20 and 35 μm, respectively. The test work performed on the 10 and 20 µm material was done in three-stage continuously-operated reactors at 70°C at a 10 % feed solids concentration and an overall feed residence time of 6 days.

High nickel extractions (>97%) were achieved over the range of particle sizes evaluated (Table 4). Final sulfide extractions ranging between 95 and 99% were observed, indicating high pyrite and pyrrhotite oxidation.

Increasing the particle size from 10 to 20 µm resulted in a reduction in copper extraction from 95 to 91 %. It is known that when using the thermophile culture there is a limitation on the feed solids concentration that could be used. In this study, with both the 10 and 20µm material, the maximum feed solids concentration which could be tolerated was 12%, which is similar to previously reported results using the thermophile culture (Gericke et al., 2010).

Table 4. Summary of bioleach results showing the effect of grind size on metals extractions

	Cu extraction (%)			Ni extraction (%)			S^{2-} extraction (%)		
Operating conditions	R1	R2	R3	R1	R2	R3	R1	R2	R3
3-stage, 70 °C, 10 µm, 6 days	83.5	92.0	95.1	98.7	99.3	99.4	98.1	98.0	99.0
3-stage, 70 °C, 20 µm, 6 days	72.4	82.0	90.7	96.3	97.4	97.4	90.6	95.9	98.3
1-stage, 70 °C, 35 µm, 3 days	52.9			87.7			82.0		
Batch, 70 °C, 35 µm, 4 days	64.4			96.1			90.9		
Batch, 70 °C, 35 µm, 5 days	72.2			97.9			91.0		
Batch, 70 °C, 35 µm, 6 days	72.8			98.1			95.0		
Batch, 70 °C, 35 µm, 9 days	71.5			97.6			94.4		

The test work on the 35 µm concentrate was performed in a single-stage continuously-operated reactor at a residence time of 3 days. The feed concentration was gradually increased from 10% to

15 %. Although a reduction in redox potential levels from around 620mV to approximately 570mV was observed, the process could be operated stably at feed solids concentrations as high as 15% (Figure 2). Once steady-state conditions were reached at 15% feed solids, samples were collected for mass balance purposes, feed addition was stopped and the reactor was operated in batch mode for a further six days. Samples were collected for analyses at regular intervals and analysed for copper and nickel extractions as indicated in Table 4.

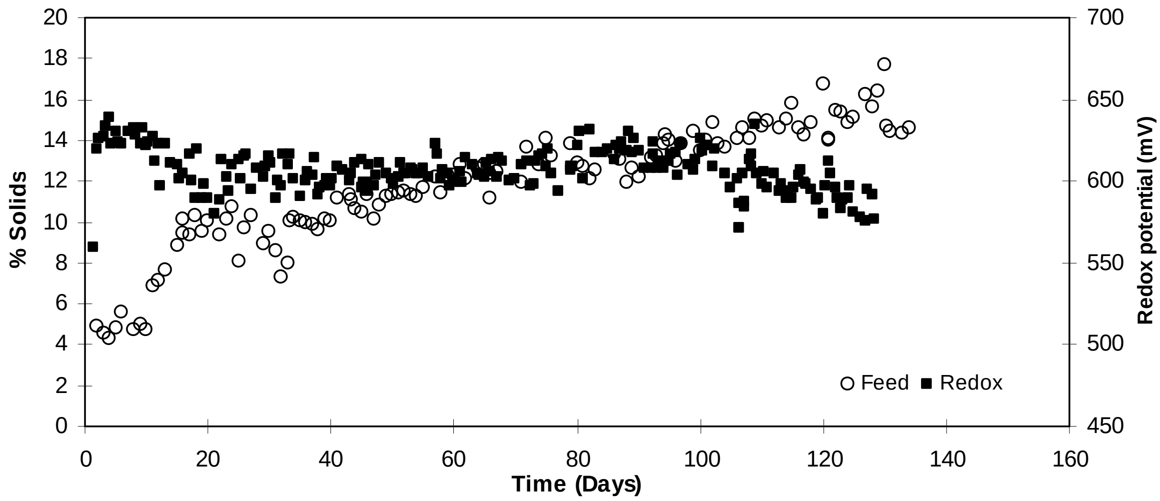

Figure 2. Time-course data showing the effect of increased feed solids concentration using concentrate with a particle size of d_{90}=35µm

It was shown that 97% Ni extraction could be obtained at a grind size of 35µm, but low Cu extractions were observed and only 72% Cu could be recovered after an extended residence time of 9 days (Table 4).

Although the coarser material did not have an impact on the final Ni extractions which could be achieved, the effect on the oxidation of chalcopyrite was pronounced and the final Cu extractions were reduced from 95% at 10µm to around 72% at 35µm. In addition, the test work demonstrated that the use of coarser material could increase the maximum feed solids concentration that can be tolerated when using the extreme thermophiles. Similar observations were made by Nemati *et al*., 2000, who showed that the presence of fine particles adversely influenced the activity of *Sulfolobus metallicus* BC, apparently by damaging the structure of the cells, resulting in their inability to oxidise pyrite.

3.2.2. *The effect of temperature on metal extractions using the thermophile culture*

Further optimisation of the process included a series of tests to determine the effect of temperature changes on the leach kinetics and extractions in a 3-stage continuously operated bioleach reactor system by varying the operating temperature between 65 and 75°C.

Results presented in Table 5 showed that higher than 97% Ni extraction could be achieved at all the temperatures evaluated. Low Cu extractions of around 91% were recorded at 65°C, whereas Cu recoveries around 96% were recorded while operating between 70 and 74°C. Increasing the temperature to 75°C resulted in a drop in the redox potential level in the first stage reactor to around 410mV, while redox potential levels of 430mV and 440mV were measured in the second and third stage reactors respectively. Operation at the lower redox levels resulted in 98% Cu recovery in the first stage reactor at a 3-day residence time compared with only 83% Cu extraction achieved in the first-stage reactor when operating at 70°C at high redox potential. A final Cu recovery of 99% was achieved while operating at the reduced redox levels compared with 95% at high redox potential. The lower sulfide conversion experienced at 75°C indicated incomplete pyrite oxidation at the reduced redox potential levels.

It was assumed that the increased Cu recoveries at 75°C were mainly the result of the reduced redox levels and not due to the operating temperature. The results indicated that operating at high temperature did not mask the effect of redox potential on Cu extractions and there is the potential to operate at reduced residence times when the redox potential of the solution is controlled.

Table 5. The effect of operating temperature on extractions and performance of the thermophile culture in a 3-stage continuously operated reactor (10% feed solids, 10µm, 6-day residence time)

	Cu extraction (%)			Ni extraction (%)			S^{2-} extraction (%)		
Temperature (°C)	R1	R2	R3	R1	R2	R3	R1	R2	R3
65	70.1	80.3	90.7	94.9	97.0	97.4	87.2	95.1	98.3
70	83.5	92.0	95.1	98.7	99.3	99.4	98.1	98.0	99.0
72	82.7	90.8	96.5	97.9	97.6	99.1	92.9	97.7	99.0
73	82.7	91.1	96.1	97.9	99.2	99.4	91.8	97.3	99.0
74	85.0	92.3	96.6	98.1	99.4	99.5	94.1	97.7	99.2
75	98.4	99.6	99.6	86.0	94.4	97.1	62.7	70.5	75.1

3.2.3. *The effect of redox potential on Cu and Ni extractions while operating at 70°C*

The results described in the previous section indicated the potential to improve the Cu leach kinetics at thermophilic conditions while operating at reduced redox levels. Further studies focused on establishing the optimum redox potential level for the extraction of Cu without compromising Ni extractions. The effect of a combination of redox control and grind size on Cu and Ni extractions while operating at 70°C was evaluated. The benchmark operating condition against which the leach kinetics was compared was the use of the thermophilic consortium at 70°C and an uncontrolled redox level.

A series of tests were performed in a single-stage continuously operated reactor at 70°C. The redox was carefully controlled to determine the effect redox potential on leach kinetics and metal extractions. The output from a redox controller was used to adjust the impeller speed to control the mass transfer supply of oxygen, thereby maintaining the redox potential at the set point.

The results indicated that faster copper leach kinetics could be achieved at 70°C when maintaining the redox potential levels between 410 and 450 mV, while the reverse was true for nickel and a reduction in nickel extraction rates was observed at redox potential levels below 460 mV (Figure 3).

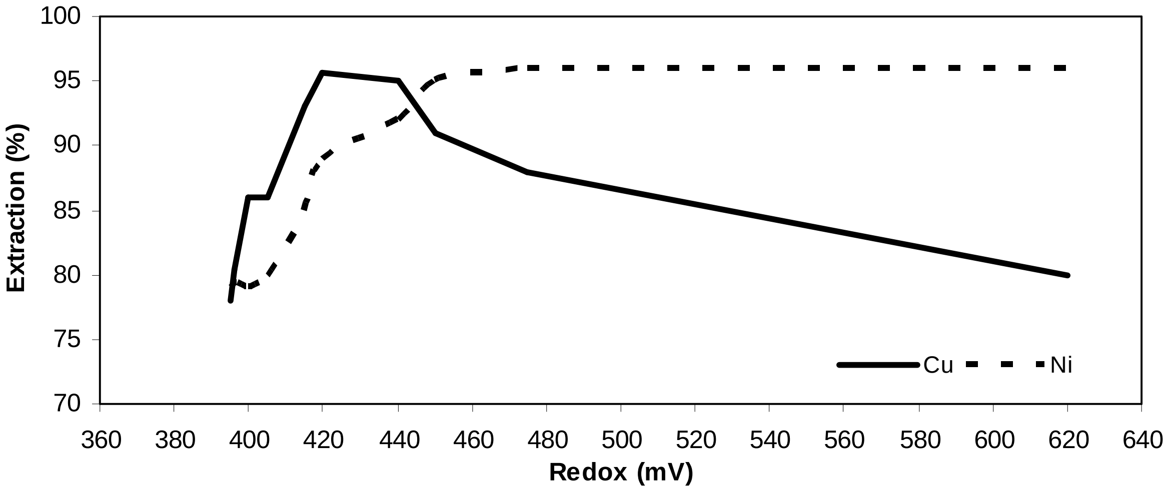

Figure 3. Effect of redox potential levels on Cu and Ni leach kinetics

Based on these results, a three-stage continuously operated reactor system was run at 70 °C and an overall 6-day residence time using concentrate milled to a particle size of d_{90} = 10 µm. The redox potential in the first-stage reactor was maintained at 430 mV, while the redox levels in the secondary stages were not controlled and 550 mV and 580 mV were measured in the second- and third-stage reactors respectively. A summary of the process conditions and extractions obtained when controlling the redox potential in the first stage reactor is presented in Table 6.

Control of the redox potential in the first-stage reactor resulted in faster copper leach kinetics, and around 96 % of the copper were recovered after three days (Table 6) compared to 83 % when the redox was not controlled (Table 5). Overall copper extractions improved from 95 % (redox not controlled) to 98 % (controlled redox). Vilcaez *et al.,* 2008 reported high leaching rates when employing *A. brierleyi* to bioleach chalcopyrite concentrates. In their case, it was concluded that the increased rate could be attributed to the accumulation of ferrous iron, which caused a reduction in both the redox levels and amount of jarosite precipitation.

The high redox levels in the secondary stages ensured that a maximum nickel extraction of over 98 % could be achieved in the second-stage reactor (Table 6). The increase in Cu leach kinetics obtained when controlling the redox potential in the first stage reactor, followed by a second stage where the redox is not controlled to ensure high Ni extractions has the advantage that a reduction in the overall feed residence time would be possible.

Table 6. Process conditions and metal extractions obtained using redox control in the first age, 10% feed solids at 70°C

	d_{90}=10µm			d_{90}=20µm		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
pH level	1.6	1.3	1.25	1.7	1.4	1.3
Redox (mV, Ag|AgCl))	430	550	580	430	550	570
Overall residence time (d)	3	4.5	6	3	4.5	6
Cu extraction (%)	96.2	97.8	98.1	92.7	95.8	96.0
Ni extraction (%)	93.8	98.4	98.7	85.1	96.9	97.9
S^{2-} extraction (%)	67.3	94.2	98.8	63.7	84.7	94.2

Additional tests focused on a series of ferric leach tests performed at 70°C at particle sizes ranging between 10 and 40µm to get an indication of the effect of particle size on final Cu extractions and leach kinetics when operating at controlled redox potential levels. The results, as shown in Figure 3, were obtained at a redox of 430mV and indicated that Cu extractions >96% could be obtained at all particle sizes evaluated. Ni extractions dropped from around 90% at a grind size of 10 µm to around 70% at particle sizes between 20 and 40µm, which is the opposite of the results observed at high redox (Table 3).

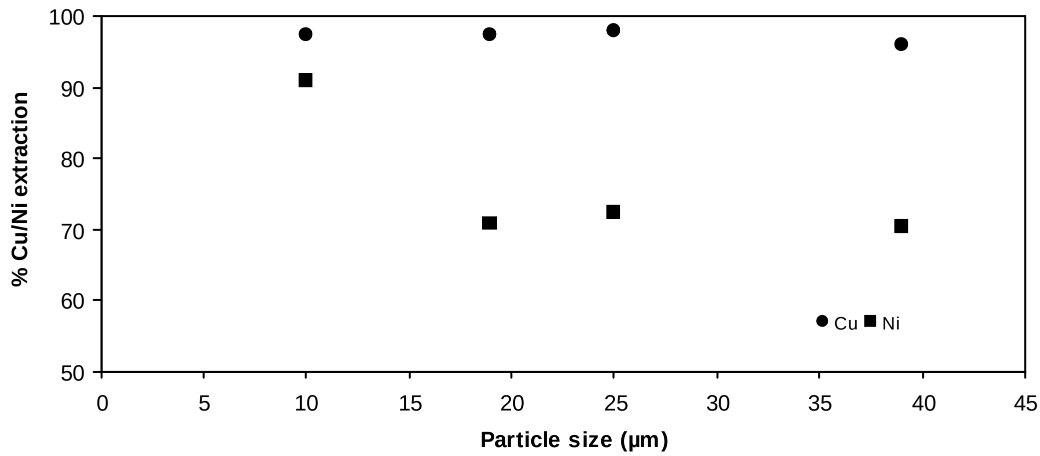

Figure 4. Ferric leach tests performed at 430mV, 70°C showing the effect of particle size on Cu and Ni extractions

Further bioleach test work was performed using concentrate milled to a particle size of d_{90}=20µm to confirm the ferric leach results. Similar operating conditions as described above were used. The redox potential in the first-stage reactor was maintained at 430 mV, while the redox levels in the secondary stages were not controlled and 550 mV and 570 mV were measured in the second- and third-stage reactors respectively (Table 6).

Control of the redox potential resulted in a copper recovery of around 92 % in the first-stage reactor compared to 72 % when operating at high redox, d_{90}=20µm. An overall copper extraction of 96 % could be achieved, compared to 90% at uncontrolled redox potential levels (Table 4). The high redox levels in the secondary stages ensured that a final nickel extraction of approximately 98 % could be achieved, similar to when operating at uncontrolled redox potential. As was the case when using 10µm material, the potential exists to operate the process at a reduced residence time.

3.2.4. *Two-stage bioleach system using mesophiles and thermophiles*

The results obtained with thermophiles indicated that acceptable Ni and Cu extractions could be obtained at 70°C. There was, however, a limitation on the feed solids concentration that could be used. Lindström and colleagues (2003) proposed a sequential two-stage process for the treatment of refractory gold concentrates, where a low temperature first stage was followed by a thermophile stage. A similar approach for the treatment of the Ni-Cu concentrate was followed and the use of the alternative bioleaching configuration, namely a two-stage bioleach system, involving a 37°C first stage with a residence time of 3 days, followed by a 70°C stage with a 3-day residence time was investigated. The system consisted of a mesophilic first stage reactor operating at a feed solids concentration of 20% and a 3-day residence time, followed by a thermophile bioleach step at a residence time of 3 days, where the latter served to leach the residual chalcopyrite copper.

Initially no inter-stage thickening of the 37°C product was conducted and the product from the mesophilic operation was fed directly into the thermophilic process. Stable operation could, however, not be maintained in the thermophile reactor, most likely due to the high total soluble metal ion concentration (60 g/L) of the liquor leaving the first stage reactor. The pulp obtained from the first stage was subsequently filtered and re-pulped before feeding it to the thermophile reactor using a separate feed tank. pH levels around 1.5 and 1.3 were measured in the mesophilic and thermophilic reactors respectively. Under these operating conditions, the redox potential increased from 580mV at 37°C to 620 mV at 70°C. The system could be stably operated over extended periods of time and promising extraction results were obtained as indicated in Table 7.

Table 7. Summary of extractions obtained in a two-stage reactor system

	Cu extraction (%)	Ni extraction (%)
1st stage (37 °C)	33	62
2nd stage (70 °C)	93	99

These results showed that the process can be operated at a feed solids concentration of 20 %. Excellent oxidative activity was maintained in the 70°C stage, as evidenced by the high redox potential levels maintained in the last reactor. It is envisaged that the leach kinetics could be further improved by operating the first stage reactor at 45°C using the moderately thermophilic culture.

The results demonstrated that a hybrid process, in which the first stage(s) of the process are operated at low operating temperatures, followed by a higher-temperature stage or stages using thermophiles, could be a feasible option for the bioleaching of Cu-Ni concentrates. Such a process has several possible advantages, including lower risk (since the thermophilic process is commercially unproven), and lower capital cost (since the major part of the process would be carried out in less expensive low-temperature reactors). One possible disadvantage is that there may be a heating requirement in moving from the mesophilic to the thermophilic process. Further assessment of the techno-economics of this process is required to confirm these observations.

3.2.5. *Optimisation of the process using the moderately thermophilic culture at 45°C*

Previous bench-scale studies carried out at Mintek demonstrated that acceptable copper recoveries could be achieved when using redox control (420mV) with moderate thermophiles (Gericke et al., 2010). An additional advantage of operating at moderately thermophilic conditions would be that high feed solids concentrations could be tolerated. Further test work was performed to assess whether the use of controlled redox with moderate thermophiles would lead to acceptable extractions for both copper and nickel.

Table. 7. Summary of the operating conditions and Cu and Ni recoveries recorded during the optimisation studies in 3-stage reactors at 45°C

Test	Reactor	Acc. residence time (days)	Feed (%)	pH	Redox (mV)
1	1	3	10	1.3	645
	2	4.5		1.3	670
	3	6		1.3	668
2	1	3	10	1.6	420
	2	4.5		1.3	612
	3	6		1.3	635
3	1	3	10	1.5	420
	2	4.5		1.6	420
	3	6		1.5	540
4	1	3	10	1.6	420
	2	4.5		1.6	420
	3	6		1.6	420
5	1	3	20	1.6	420
	2	4.5		1.6	420
	3	6		1.6	420
6	1	3	20	1.5	420
	2	4		1.5	420
	3	6		1.2	580
	4	7		1.1	615

Tests 1 to 4 were performed at 45°C at a feed solids concentration of 10% in continuously operated 3-stage reactor systems to evaluate the effect of redox levels on Cu and Ni extractions, while test 5 was performed at a feed solids concentration of 20% to assess the ability of the culture to perform at high feed solids concentrations. A summary of the operating conditions is provided in Table 7.

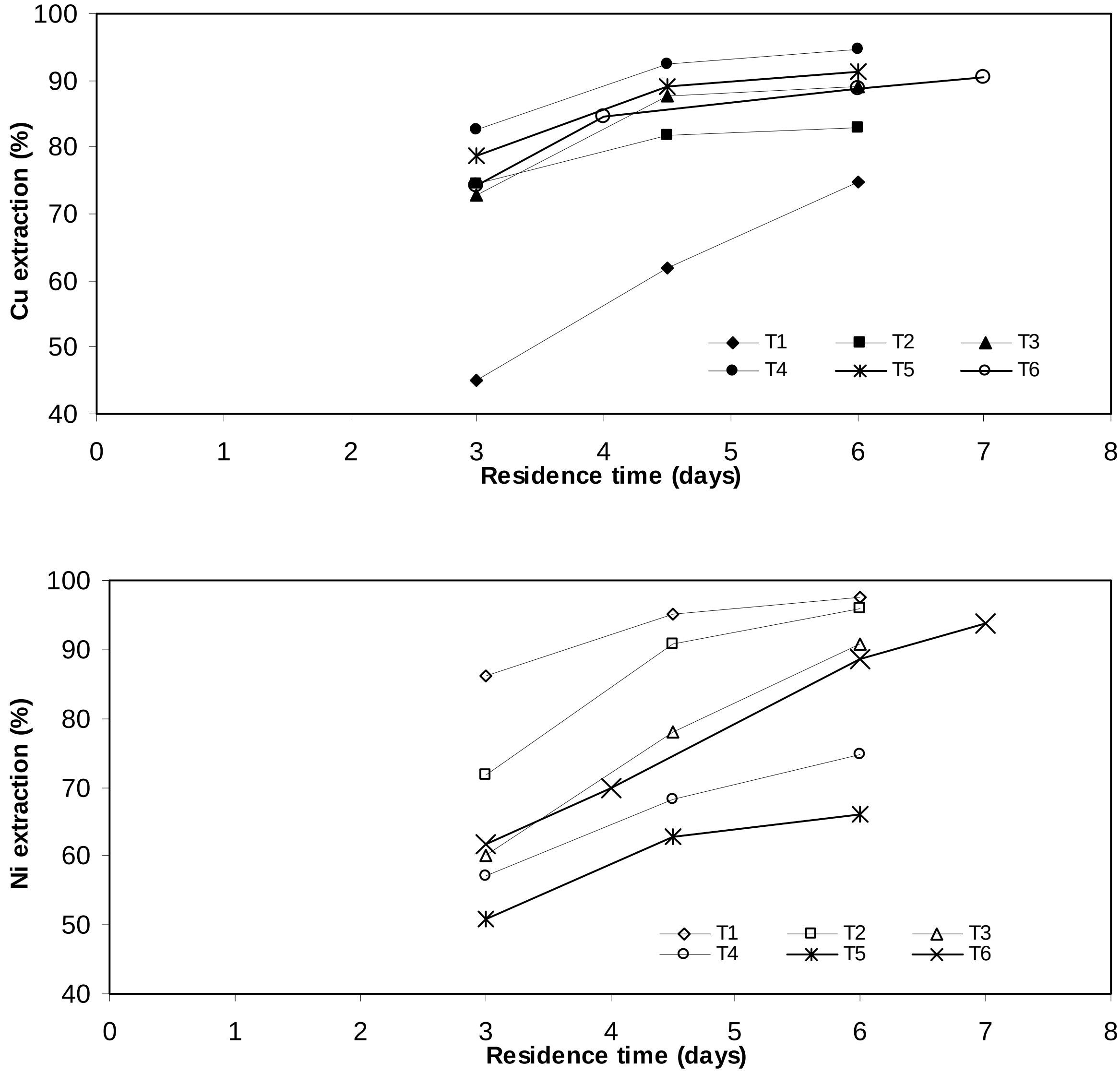

Figure 5. Cu and Ni extractions obtained at 45°C at different redox potential levels in 3-stage continuously operated reactor systems

The results presented in Figure 5 showed that while operating at high redox levels, 98% Ni and 75% Cu could be recovered (Test 1). An increase in the copper leach kinetics was observed when the redox potential in the first stage reactor was reduced to 420mV (Test 2). Cu extractions were further improved to 89 and 95% after reducing the redox potential in the second (Test 3) and third stages (Test 4) respectively. The increase in Cu recoveries observed, however, coincided with reduced Ni extractions and only 75% Ni could be recovered while operating at 420mV (Test 4).

Although the data showed that Cu recoveries could be improved by redox control, it was clear that secondary reactors operating at high redox levels would be necessary to maximise Ni recoveries. The concept was assessed in a 4-stage reactor system at 20% feed solids concentration and a 7-day overall residence time (Test 6). The redox potential in the first 2 stages was controlled at 420 mV, whereas the redox in the third and fourth stages was allowed to increase to 580 and 615mV respectively. The results presented in Figure 5 show that 91% Cu and 94% Ni could be recovered under these conditions. It is anticipated that further optimisation of redox levels, residence time and reactor configuration could lead to further improvements in both Ni and Cu extractions.

4. CONCLUSIONS

In this paper different bioleaching strategies for the treatment of polymetallic Ni-Cu concentrates were assessed at 45 and 70°C. It was evident from the study that copper dissolution from chalcopyrite was favoured by leaching at a redox potential level around 420 to 430 mV compared to leaching at around 600 mV, while the reverse was true for pentlandite. Potential bioleach process options which were highlighted included:

- Thermophilic bioleaching at 70°C, 10% feed solids, a particle size of d_{90}=10μm at an overall 6-day residence time without redox control. Cu and Ni extractions of 95 and 99% respectively could be obtained.
- Thermophilic leaching where the redox potential in the first stage reactor was controlled to ensure maximum Cu extraction, while the redox potential in the secondary reactors were not controlled to ensure maximum Ni extractions. In this

scenario an increase in the rate of chalcopyrite leaching was demonstrated, bigger grind sizes could be used and there was potential for reduction of the overall residence time, which could result in a smaller plant with lower capital and operating cost.

- Bioleaching using a moderately thermophilic culture at 45°C, using a combination of high and low redox levels and a grind size of d_{90}=10µm. An advantage of the lower temperature process was the potential to operate at increased feed solids concentrations of 20%.

5. ACKNOWLEDGMENTS

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