

Development of a process for the separation of zinc and copper from sulfuric liquor obtained from the leaching of an industrial residue by solvent extraction

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ABSTRACT

This paper describes a study of the separation of zinc and copper from the leach liquor generated in the treatment of the zinc residue (29.6 g/L Zn and 37.4 g/L Cu) by liquid–liquid extraction. In it, the influence of the extractant type and concentration, aqueous phase acidity, contact time and stripping agent concentration were investigated. Organophosphorus extractants (D2EHPA, IONQUEST®801 and CYANEX®272) and the chelating extractants (LIX®63, LIX®984N and LIX®612N-LV) were also investigated. The organophosphorus reagents are selective for zinc, while the chelating extractants are selective for copper. In the experiment, D2EHPA was found to be the best extractant. A sulfuric acid solution was used in the stripping study. Five continuous experiments were carried out until an optimal condition for the separation of the metals Zn and Cu was achieved. Experiment 5 was carried out in three extraction steps, three scrubbing stages and five stripping stages. In this experiment, a pregnant strip solution containing 125 g/L Zn and 0.01 g/L Cu was obtained and the concentration of the metals in the raffinate was 28.3 g/L Cu and 0.49 g/L Zn.

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1. Introduction

Metallurgical Extraction is employed to obtain pure metals from ores or byproducts. Metallic zinc production from sulfide zinc concentrate comprises roast, leach and electrowinning steps. In the leaching step, metals with lower concentration such as cadmium, nickel and cobalt are leached with zinc. The liquor purification, typically carried out through cementation, produces a residue containing high levels of zinc, cadmium, and copper. Generally, the treatment of this residue in the recovery of zinc produces other residues that are stockpiled, therefore resulting in an environmental liability. The recovery of metals from such secondary source reduces the environmental impact and could bring a financial return to the metal producers (Jha et al., 2001).

A solid residue containing 26.9% Zn, 36.9% Cu, 1.9% Cd, 0.18% Co and 0.21% Ni was obtained from a hydrometallurgical zinc facility. This residue was leached with a sulfuric acid solution resulting in a sulfuric liquor containing 29.6 g/L Zn, 37.4 g/L Cu, 1.94 g/L Cd, 0.127 g/L Co and 0.100 g/L Ni.

Zinc and copper can be separated from sulfuric liquors by cementation or liquid–liquid extraction. In the former, the high copper content of the solution consumes an undesirably high

amount of reagent (Dienstbach et al., 1989). The separation of the metals is therefore more appropriate when done through solvent extraction. The solvent extraction technique has become essential to the hydrometallurgical industry due to a growing demand for high purity metals, rigid environmental regulations, the need for lower production costs, and the diminishing production in high-grade ore reserves, this leads to the necessity of the treatment of ores of lower grade and greater complexity (Alamdari, 2004; Owusu, 1998).

Flett (2005) proposed that D2EHPA and Cyanex 272 (acid extractants) should be applied for application in the cobalt/nickel separation, as well as for zinc and rare earth extraction. IONQUEST is frequently used in the cobalt/nickel separation; however zinc is mostly extracted with the use of these organophosphorus extractants (Sole et al., 2005). LIX reagents (acid chelating extractants) are proposed for copper and nickel extraction. According to Zhang and collaborators (1996), LIX®63 was the first extractant to be commercialized specifically for copper extraction.

In the present study, the organophosphorus extractants (D2EHPA, IONQUEST®801 and CYANEX®272) and the chelating extractants (LIX®63, LIX®984N and LIX®612N-LV) were investigated for Zn/Cu separation. The following process variables: aqueous phase acidity, D2EHPA concentration, contact time and stripping agent concentration (sulfuric acid) were tested using D2EHPA as the extractant. Five continuous experiments were conducted until an optimal condition for the separation of the metals Zn and Cu was achieved.

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2. Experimental

2.1. Reagents and solutions

Di-2-ethylhexyl phosphoric acid (D2EHPA), 97 wt.%, and 2-ethylhexyl-mono-2-ethylhexylester, 99 wt.%, were manufactured by Albright and Wilson Americas and supplied by Pecos Brasil Ltda. Bis-2,4,4-trimethylpentyl-phosphinic acid (CYANEX®272), 99 wt.%, was manufactured by Cytec Canada Inc, and supplied by Cytec do Brasil Ltda.

LIX®63, LIX®984 and LIX®612N-LV are manufactured by Cognis and were supplied by Cognis do Brasil Ltda. LIX®63 is 5,8-diethyl-7-hydroxydodecane-6-oxime (2.27 mol/L oxime). LIX®984N is a mixture of oximes: 5-nonylsalicylaloxime and 2-hydroxy-5-nonylaceto-phenone oxime (1.66 mol/L oxime). LIX®612N-LV is a proprietary mixture of an extractant and a high flash point hydrocarbon diluent with low viscosity.

Exxsol®D-100 (purified kerosene), used as diluent, was supplied by Exxsol Química.

The sulfuric acid (H₂SO₄) used in the stripping experiments and the ammonium hydroxide (NH₄OH) used for pH control were of analytical grade. The solutions were prepared with distilled water.

The sulfuric liquor containing 29.6 g/L Zn, 37.4 g/L Cu, 1.94 g/L Co and 0.100 g/L Ni was obtained from the leaching of the residue of zinc and copper generated by the zinc production. The residue is a zinc and copper secondary source, containing 26.9% Zn, 36.9% Cu and other metals, such as Cd, Co and Ni. The residue was generated in the purification of the liquor produced in the leaching stage of the zinc ore.

2.2. Batch experiments

Extraction and stripping experiments were carried out in an agitated reactor (150 mL beaker – 5.3 cm diameter) at 500 rpm agitation at room temperature (~25 °C), using equal volumes (20 mL) of aqueous and organic phases. During the extraction experiments, the pH of the aqueous phase was controlled with an ammonium hydroxide solution (1–3 mol/L). After contact, the aqueous/organic mixture was transferred to a separation funnel and the phases were collected separately. The metal content in each phase was determined by atomic absorption spectrometry. Unless specified otherwise, the O/A phase ratio volume basis was 1 and the equilibrium pH was 2. The experimental error including the analytical error was 3% at a confidence level of 95% of confidence level.

2.3. Continuous experiments

Five continuous experiments were carried out until an optimal condition for the separation of the metals Zn and Cu was achieved. The continuous experiments were carried out by using D2EHPA as the extractant, in mixer-settler polycarbonate units, with mixers of 70 mL and settlers of 260 mL.

The experiments from 1 to 4 were carried out with a solution, prepared in a laboratory, simulating the actual industrial liquor. These experiments were carried out in three extraction stages, three scrubbing stages and five stripping stages. Experiment 5, was done with the industrial liquor in the same conditions as those of that in Experiment 4, but presenting better results.

Peristaltic pumps were used to feed the zinc and organic solutions, the scrubbing solution (H₂SO₄ 0.1 mol/L) and the stripping solution (H₂SO₄ 2 mol/L) to the circuit. Ammonia gas (20 wt.%) was used for pH adjustment in the extraction stage. The control of the system stability was evaluated through zinc/copper determination every hour in the exit flows. Every hour, the flow rates of the feeding solutions were also checked. During the development of

the process, the metals Zn, Cu, Cd, Co and Ni concentrations in the aqueous phase were measured with the use of an atomic absorption spectrophotometer.

3. Results and discussion

3.1. Batch experiments

3.1.1. Extraction step

Six cationic extraction agents were investigated: three organophosphorus acids (D2EHPA, IONQUEST®801 and CYANEX®272) and three chelating acids with oximes functional groups (LIX®63, LIX®612N-LV and LIX 984®N). The concentration of the organophosphorus extractants was 1 mol/L. The concentration of the LIX extractants was 1 mol/L oxime. The equilibrium pH was 3 and the agitation time was 15 min. The results of these experiments are shown in Table 1.

D2EHPA, IONQUEST®801 and CYANEX®272 are selective for zinc, while LIX®63, LIX®612N-LV and LIX 984®N are selective for copper. In metals separation, the separation factor is more important than the extraction coefficient itself. Experiments showed that the coalescence time for organophosphorus extractants was lower than the coalescence time for chelating extractants (<30 s and 8 min, respectively). This may be due to the high LIX concentration used in the experiments. A good separation factor was obtained with all extractants tested. As D2EHPA is less expensive than the other extractants investigated, this reagent was selected for further tests.

3.1.1.1. Contact time. The aqueous and organic contact time adopted was between 10 and 15 min. Under a more efficient pH control, a shorter time may be sufficient if the accomplishment of the extraction equilibrium is desired.

3.1.1.2. Equilibrium pH. After choosing the desired extractant, the influence of the aqueous phase acidity on the metals separation was investigated. The effect of the equilibrium pH was investigated between 0.70 (without NH₄OH addition) and pH 3.5. The optimum contact time varied from 5 min (without correction of pH) to 15 min (pH 3.5). Results obtained are shown in Fig. 1. The equilibrium pH is an important variable in the metals separation. Above pH 2, copper extraction increases while the Zn/Cu separation factor decreases. At low pH, the zinc extraction is not efficient.

3.1.1.3. Concentration of the extractant. The effect of the concentration of the extractant in the Zn/Cu separation was investigated between 0.25 mol/L and 1.0 mol/L D2EHPA (Fig. 2). The equilibrium pH was maintained at 2 and the contact time varied from 10 to 15 min. The experiments indicated that zinc extraction increases from 30% to 88% when the D2EHPA concentration increases from 0.25 mol/L to 1.0 mol/L. In the range of the D2EHPA concentration investigated, copper extraction varied from 0.3% to 2.1%. The con-

Table 1
Effect of the extractant on Zn, Cu, Cd, Co and Ni extraction.

Extractant	pH _{eq.}	Separation factors		Extraction (%)				
		Zn/Cu	Cu/Zn	Zn	Cu	Cd	Ni	Co
LIX®63	3.0	–	62	4.1	72.5	18.0	<0.1	<0.1
LIX®612N-LV	2.9	–	94	6.4	86.6	13.4	2.4	1.6
LIX®948N	3.1	–	37	9.5	79.4	14.4	<0.1	0.8
D2EHPA	3.0	296	–	94.5	5.5	1.0	1.4	<0.1
IONQUEST®801	3.0	323	–	88.9	2.4	3.1	<0.1	0.8
CYANEX®272	3.0	361	–	70.9	0.7	11.1	<0.1	3.1

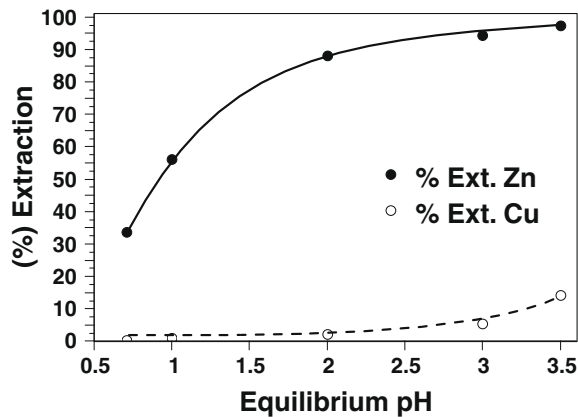


Fig. 1. Influence of the equilibrium pH in the extraction of Zn and Cu with 1 mol/L D2EHPA.

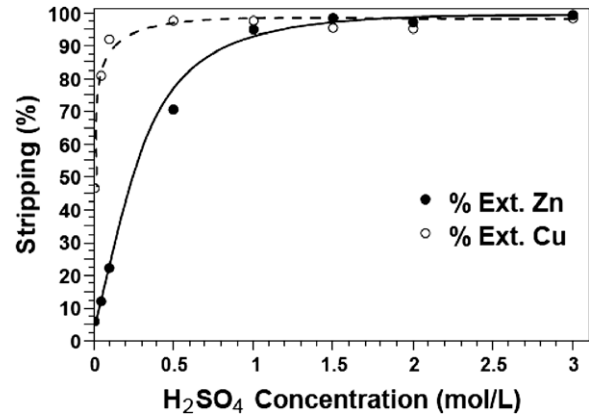


Fig. 3. Influence of H₂SO₄ concentration in the Zn and Cu stripping from 1 mol/L D2EHPA.

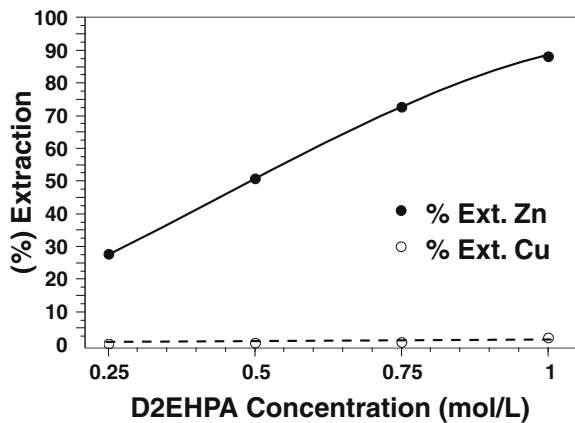


Fig. 2. Influence of the D2EHPA concentration in the extraction of Zn and Cu.

centration of D2EHPA selected for the remainder of the study was 1.0 mol/L.

3.1.2. Stripping step

The stripping experiments were carried out with a sulfuric acid solution having its concentration investigated from 0.01 mol/L to 3.0 mol/L, using a volumetric phase ratio (O/A) 1. In the experiments the contact time was 5 min and the separation time was shorter than 30 s. The loaded solvent used in the stripping experiments was obtained through two successive discontinuous contacts of the solvent with the liquor maintaining an equilibrium pH 2. Its content was 33 g/L Zn, 0.14 g/L Cu, 0.003 g/L Cd, and less than 0.001 g/L of Co and Ni.

As shown in Fig. 3, copper is easier to strip than zinc. For 0.05 mol/L H₂SO₄, the percentages of the metals stripped reached 81% Cu and 12% Zn. This indicates that co-extracted copper can be scrubbed in a counter current mixer-settler system using a low H₂SO₄ concentration. Zinc may be subsequently stripped at a higher H₂SO₄ concentration.

3.1.3. McCabe–Thiele diagrams

Using lab test results, extraction and stripping isotherms (equilibrium curves) were constructed and McCabe–Thiele Diagrams were drawn to determine the theoretical number of stages and the volumetric feed ratio of the liquor and solvent for the continuous experiments. The equilibrium curves were drawn according to

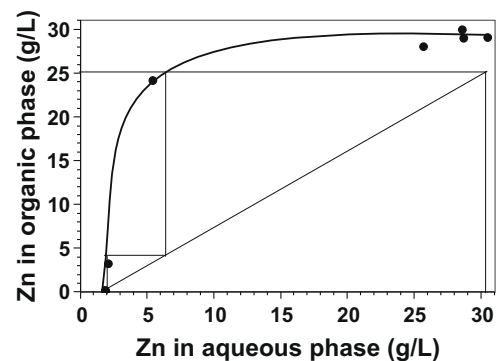


Fig. 4a. Isotherm/McCabe–Thiele for Zn extraction from the sulfuric liquor with 1 mol/L D2EHPA.

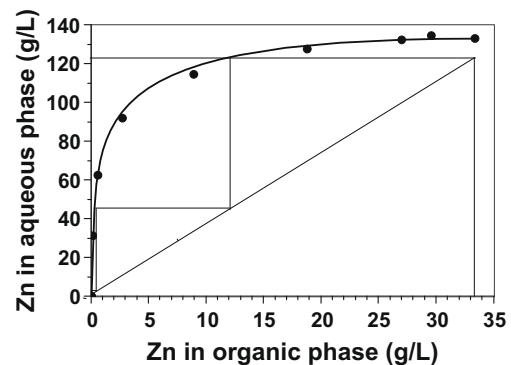


Fig. 4b. Isotherm/McCabe–Thiele for Zn stripping from the loaded 1 mol/L D2EHPA with 2 mol/L H₂SO₄.

the successive contact technique using phase ratio 1. The McCabe–Thiele diagrams are shown in Figs. 4a and 4b.

Fig. 4a indicates that three extraction stages at a phase ratio A/O 0.8 volume basis will quantitatively extract zinc from the aqueous phase. For a loaded solvent containing 33 g/L Zn, it requires three stripping stages (Fig. 4b).

3.1.4. Continuous experiments

The batch experiments indicated that zinc is more easily extracted than copper. Therefore, the objective of the continuous

experiments was to lead zinc to the organic phase, while the other metals are kept in the raffinate. Five continuous experiments were carried out until an optimal condition for the separation of the metals Zn and Cu was achieved.

The experimental set-up comprised three steps: extraction, scrubbing and stripping having their variables continuously adjusted in consecutive runs until the desired yields and grades were achieved.

Experiment 1 was carried out in two extraction stages, two scrubbing stages and five stripping stages for 30 h. The residence time of the solution in the mixer in these steps was 6, 8 and 8 min, respectively. Under these conditions, the zinc concentration in the stripping liquor was 106 g/L. In order to increase this concentration, the residence time was augmented to 10, 14 and 14 min, respectively. However, the copper concentration in the stripping liquor increased from 1 to 3 g/L, which was undesirable (Experiment 2).

Experiments 3–5 comprised three extraction stages, three scrubbing stages and five stripping stages (Fig. 5). The residence time in the mixer for these steps was 6 min, 8 min and 8 min, respectively. In Experiment 3, the flow rate of the zinc liquor and of the scrubbing solution was 4.4 mL/min and 1.0 mL/min, respectively. Under these conditions, the copper concentration in the stripping liquor was 0,170 g/L. In order to reduce this concentration, in Experiment 4, the flow rate of the scrubbing solution increased to 1.4 mL/min. After 13 h of experiment, 0.35 g/L Zn and 28.5 g/L Cu was obtained in the raffinate while in the pregnant stripping solution, the zinc and copper concentrations were 0.160 g/L of Cu and 125 g/L of Zn.

Experiment 5 was carried out with the industrial liquor mentioned previously, in the same condition set for Experiment 4 (Table 2). The extraction occurred in stages 1–3. The aqueous solution containing zinc was fed into the third stage whereas the organic solution was fed into the first stage. The scrubbing solution (0.1 mol/L H₂SO₄) was added in the 6th stage aiming at removing the co-extracted copper. It was combined with the industrial solution and then removed in stage 1. The pH was controlled in pH 2 in stages 2 and 3 of the extraction step, through the addition of ammonia gas. In the first stage, the pH observed was 1.6.

The zinc present in the loaded organic phase, after passing through the scrubbing stage, was fed into the stripping step, stages 7–11. The stripping solution (2.0 mol/L H₂SO₄) was fed into the 11th stage and the pregnant stripping solution was removed in stage 7. The organic effluent was fed back into the circuit without any additional treatment.

A high efficiency of the proposed separation process is observed in Table 3. A raffinate containing 0.49 g/L Zn and 28.6 g/L Cu and a pregnant stripping solution containing 125 g/L Zn and 0.01 g/L Cu was obtained.

Table 2

Operational conditions of Experiments 4 and 5.

Step	Solution		Flow rate (mL/min)		Contact time (min)	Number of stage
	Reagent	Concentration (mol/L)	Aqueous	Organic		
Extraction	D2EHPA	1	4.4	7.3	6	3
Scrubbing	H ₂ SO ₄	0.1	1.4	7.3	8	3
Stripping	H ₂ SO ₄	2	1.0	7.3	8	5

Table 3

Metals content in the liquor and in the exit flows in the Experiment 5.

Sample	Zn (g/L)	Cu (g/L)	Cd (g/L)	Ni (g/L)	Co (g/L)
Industrial liquor	29.6	37.4	1.98	0.100	0.127
Raffinate	0.49	28.35	1.48	0.080	0.100
Pregnant stripping solution	125	0.01	<0.005	<0.005	<0.005
Regenerated organic	<0.005	<0.005	<0.001	<0.001	<0.001

The profiles of the zinc and copper content in the aqueous and organic phases of the extraction, scrubbing and stripping steps are shown in Figs. 6a and 6b, according to the results obtained in Experiment 5. Under these conditions, in the extraction step, the pH varied from 1.6 in the first stage to 2 in the second and third stage. The flow rate of the industrial zinc liquor was 4.4 mL/min and the ratios of the aqueous/organic phases in the extraction and stripping steps were 0.6 and 7.3, respectively.

3.1.5. Mass balance

The mass balance for Experiment 5 is presented below. The nomenclature used is also defined.

[M_{FI}] = Metal concentration in the feeding liquor.

[M_{Raf}] = Metal concentration in the raffinate.

[M_{SS}] = Metal concentration in the scrubbing solution.

[M_{Io}] = Metal concentration in the initial organic.

[M_{Lo}] = Metal concentration in the loaded organic.

[M_{So}] = Metal concentration in the stripped organic.

[M_{Ps}] = Metal concentration in the pregnant stripping solution.

A = Aqueous flow rate = 4.4 mL/min.

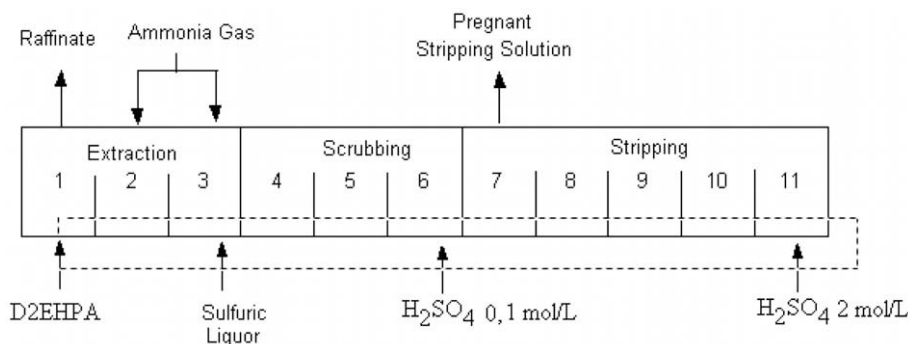
O = Organic flow rate = 7.3 mL/min.

Sc = Scrubbing solution flow rate = 1.4 mL/min.

St = Stripping solution flow rate = 1.0 mL/min.

R = Raffinate flow rate = (A + Sc) = 5.8 mL/min.

M = Zn or Cu

**Fig. 5.** Continuous counter-current circuit for Zn/Cu separation – Experiments 3–5.

The mass balance for the metals results in:

3.1.5.1. Extraction step.

$$A[M_{Fi}] = R[M_{Raf}] + O[M_{9m}]$$

where

$$[Zn_{Fi}] = 29.6 \text{ g/L}$$

$$[Cu_{Fi}] = 37.4 \text{ g/L}$$

$$[Zn_{Raf}] = 0.49 \text{ g/L}$$

$$[Cu_{Raf}] = 28.35 \text{ g/L}$$

Mass balance for Zn:

$$4.4 \times 29.6 = 5.8 \times 0.49 + 7.3$$

$$[Zn_{Lo}]$$

$$130.24 = 2.84 + 7.3 [Zn_{Lo}]$$

$$[Zn_{Lo}] = 17.5 \text{ g/L}$$

Mass balance for Cu:

$$4.4 \times 37.4 = 5.8 \times 28.35 + 7.3$$

$$[Cu_{Lo}]$$

$$164.6 = 164.43 + 7.3 [Cu_{Lo}]$$

$$[Cu_{Lo}] = 0.02 \text{ g/L}$$

3.1.5.2. Stripping step.

$$O[M_{Lo}] = O[M_{So}] + St[M_{Ps}]$$

where

$$[Zn_{So}] < 0.005 \text{ g/L}$$

$$[Cu_{So}] < 0.005 \text{ g/L}$$

$$[Zn_{Lo}] = 17.5 \text{ g/L}$$

$$[Cu_{Lo}] = 0.02 \text{ g/L}$$

Mass balance for Zn:

$$7.3 \times 17.5 = 7.3 \times 0.005 + 1.0$$

$$[Zn_{Ps}]$$

$$127.75 = 0.0365 + 1.0 [Zn_{Ps}]$$

$$[Zn_{Ps}] = 127.7 \text{ g/L}$$

Mass balance for Cu:

$$7.3 \times 0.02 = 7.3 \times 0.005 + 1.0$$

$$[Cu_{Ps}]$$

$$0.146 = 0.0365 + 1.0 [Cu_{Ps}]$$

$$[Cu_{Ps}] = 0.11 \text{ g/L}$$

The result of the experiments indicate:

$$[Zn_{Lo}] = 14.9 \text{ g/L}$$

$$[Cu_{Lo}] < 0.005 \text{ g/L}$$

$$[Zn_{Ps}] = 125 \text{ g/L}$$

$$[Cu_{Ps}] = 0.010 \text{ g/L}$$

A quantitative analysis of the outcome of Experiment 5 and the mass balance established in order to check the efficiency of the process is depicted in Table 4.

The mass balance indicated results similar to those obtained analytically for Zn. For Cu the figures obtained through mass balance, were higher than those obtained analytically. This occurs given the sensitivity of the methodology employed. The content of Cu in the raffinate used in the mass balance was 28.35 g/L. If we consider a raffinate containing 28.37 g/L Cu, the Cu content in the loaded organic (Cu_{Lo}) will be 0.007 g/L, and in the pregnant stripping solution (Cu_{Ps}), the value will reach 0.015 g/L. As can be

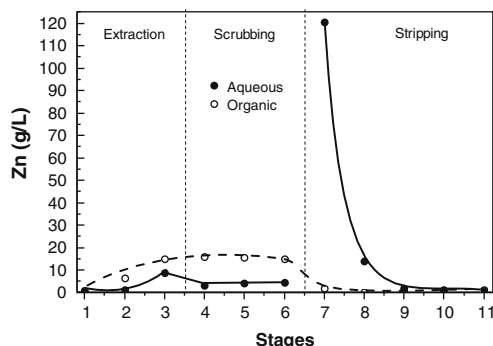


Fig. 6a. Profile of the zinc concentration of the extraction, scrubbing and stripping steps.

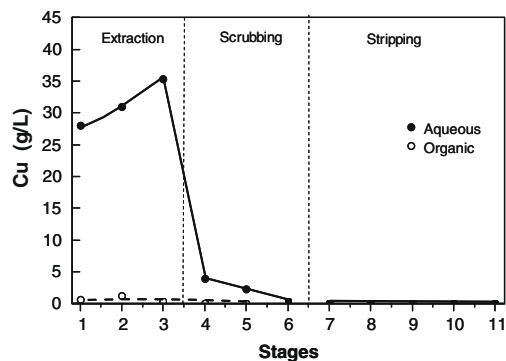


Fig. 6b. Profile of the copper concentration of the extraction, scrubbing and stripping steps.

Table 4

Mass balance for Experiment 5.

Results	Extraction		Stripping	
	Zn _{Lo}	Cu _{Lo}	Zn _{Ps}	Cu _{Ps}
Analysis (g/L)	14.9	0.005	125	0.010
Mass balance (g/L)	17.5	0.02	127.7	0.11

noted, these values are approximate the ones found analytically – 0.005 g/L and 0.010 g/L, respectively. Thus, an analytical difference smaller than 0.1% in the Cu content in the raffinate, which is an acceptable analytical error, is enough to adjust the mass balance of the analytical data obtained for Cu in the loaded organic and in the pregnant stripping solution as well.

4. Conclusions

The extractants of the LIX group (LIX[®]63, LIX[®]612N-LV and LIX 984[®]N) extract preferentially copper, while organophosphorus extractants are selective for zinc. Organophosphorus extractants (D2EHPA, IONQUEST[®]801 and CYANEX[®]272) presented higher Zn/Cu separation factors when compared with the chelating extractants investigated.

For D2EHPA, IONQUEST[®]801 and CYANEX[®]272 Zn/Cu separation factors of about 296, 323 and 361, respectively, were obtained. For the chelating extractants, the separation factor was about 62 for LIX[®]63, 94 for LIX[®]612N-LV and 37 for LIX[®]984N. Further investigations carried out with D2EHPA indicated an ideal equilibrium pH of about 2.

The stripping experiments using sulfuric acid as the stripping agent indicated that the stripping of copper outdid the stripping of zinc, indicating that the co-extracted copper can be removed from the organic phase in the scrubbing step using diluted sulfuric acid whereas Zinc can be stripped with a more concentrated sulfuric acid solution.

After the optimization of the process of separation of zinc and copper from the sulfuric liquor through solvent extraction, the continuous experiment comprised three extraction stages, three scrubbing stages and five stripping stages. A pregnant stripping solution containing 125 g/L Zn, and 0.05 g/L Cu, with less than 0.005 g/L Cd, Co and Ni, from a solution containing 29.6 g/L Zn, 37.4 g/L Cu, 1.94 g/L Cd, 0.127 g/L Co and 0.100 g/L Ni was obtained. The concentration of the metals in the raffinate was 28.3 g/L Cu, 0.49 g/L Zn, 1.48 g/L Cd, 0.08 g/L Ni and 0.10 g/L Co. Studies contemplated the technical feasibility of the separation of zinc and copper from the leaching liquor obtained in the treatment of the zinc residue by liquid–liquid extraction.

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References

- Alamdari, E.K., 2004. Synergistic effect of MEHPA on co-extraction of zinc and cadmium with DEHPA. *Minerals Engineering* 17, 89–92.
- Dienstbach, U., Moulard J., Zuliani, P., 1989. Separate treatment of cottrell dust at Kidd Creek. In: Proc. 28th Annual Conf. Metallurgists of Cim. Halifax, Canada.
- Flett, D.S., 2005. Solvent extraction in hydrometallurgy: the role of organophosphorus extractants. *Journal of Organometallic Chemistry* 690, 2426–2438.
- Jha, M.K., Kumar, V., Singh, R.J., 2001. Review of hydrometallurgical recovery of zinc from industrial wastes. *Resources, Conservation and Recycling* 33, 1–22.
- Owusu, G., 1998. Selective extractions of Zn and Cd from Zn–Cd–Co–Ni sulphate solution using di-2-ethylhexyl phosphoric acid extractant. *Hydrometallurgical* 47, 205–215.
- Sole, K.C., Feather, A.M., Cole, P.M., 2005. Solvent extraction in southern Africa: an update of some recent hydrometallurgical developments. *Hydrometallurgical* 78, 52–78.
- Zhang, P., Inoune, K., Yoshizuka, K., Tsuyana, H., 1996. Extraction and selective stripping of molybdenum(VI) and vanadium(IV) from sulfuric acid solution containing aluminum(III), cobalt(II), nickel(II) and iron(III) by LIX 63 in Exxsol D80. *Hydrometallurgical* 41, 45–53.