



# Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

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## Synopsis

Inorganic acids such as sulphuric acid have found use together with certain reducing agents in leaching of copper-cobalt oxide ores. These reagents are not ideal due to the adverse effect the inorganic acids generally have on the environment and the high costs of the reducing agents. In this study a copper-cobalt oxide ore from the Central African Copperbelt was leached in two different environments; sulphuric acid in conjunction with hydrogen peroxide as a reducing agent and tartaric acid. The effects of acid concentration, reducing agent concentration, and temperature were independently determined for both leaching environments. The sulphuric acid concentration was varied between 0.4 M and 1.2 M and the concentration of hydrogen peroxide between 4.0 M and 6.5 M, while the tartaric acid concentration was varied between 0.15 M and 0.35 M. The temperature was varied between 20°C and 50°C. The results showed that the extraction of both copper and cobalt increased with sulphuric acid concentration, reaching a peak at approximately 0.8 M and then decreasing at higher acid concentrations. A similar increase and decrease in metal extraction was observed when the reducing agent was increased. In leaching with tartaric acid, the extraction of cobalt was much higher than that of copper, although extraction of both metals increased with acid concentration. Additions of small amounts of hydrogen peroxide were found to increase cobalt extraction in tartaric acid but had a minimal effect on copper. An increase in the solution temperature had a significant effect in the organic acid environment, with the effect on cobalt extraction being much more pronounced than on copper.

## Keywords

leaching, copper, cobalt, sulphuric acid, hydrogen peroxide, tartaric acid, reducing agent.

## Introduction

Copper and cobalt are commodities of great economic value. Copper derives its value from its outstanding properties which include high electrical and thermal conductivity, malleability, and toughness. Copper is widely used in electrical cabling, piping, and the construction industry. Cobalt owes its value to the fact that it can maintain its ferromagnetism up to temperatures higher than any other metal, and to its superior catalytic qualities. Cobalt is widely used in the manufacture of magnets, catalysts, and batteries. It is also used as a pigment in paints and as an alloying element in steel production.

The Central African Copperbelt hosts 40% of the world's cobalt reserves and 10% of the world's copper reserves. The two countries that lie on the Copperbelt, the Democratic Republic of Congo (DRC) and Zambia, produce about half of the world's copper-cobalt ore (Crundwell *et al.*, 2011). The DRC is said to be the biggest miner of these ores, although the largest cobalt refinery is in China (Miller, 2009). Zambia and the DRC have a very important role to play in supplying global copper and cobalt requirements.

Escalating global demand for copper and cobalt has forced companies to increasingly exploit lower-grade ores. However, most of these low-grade ores are processed at very high costs, since large volumes have to be processed. The methods applied for the extraction of copper and cobalt from the copper-cobalt oxide ores of the Central African Copperbelt include (i) heap leaching of the low-grade ores, (ii) upgrading of the ores by flotation prior to leaching, and (iii) direct ore leaching using sulphuric acid. All these methods have inherent problems. For instance, heap leaching often has low rates of recovery, the inclusion of a flotation stage prior to leaching is costly, and direct ore leaching consumes large volumes of acid.

The main cobalt-bearing mineral in the copper-cobalt oxide ore deposits of the DRC is heterogenite ( $\text{CoO} \cdot 2\text{Co}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$ ). Copper typically occurs as chrysocolla ( $\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$ ) and malachite [ $\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ ] (Crundwell *et al.*, 2011). Minor amount of copper silicates such as diopside ( $\text{CuSiO}_3 \cdot \text{H}_2\text{O}$ ), katangite ( $\text{CuS}_{13}\text{O}_9 \cdot n\text{H}_2\text{O}$ ), and carbonates such as azurite ( $\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$ ) also occur (Prasad, 1989). The main oxides are listed in Table I.

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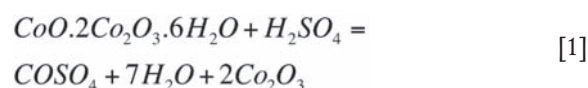
## Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

Table I

**Primary copper and cobalt oxides found in copper-cobalt ores of the Democratic Republic of Congo (Prasad, 1989)**

Oxides of copper		Oxides of Cobalt	
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	Heterogenite	$(\text{CO}_2\text{O}_3 \cdot \text{CuO})\text{H}_2\text{O}$
Cuprite	$\text{Cu}_2\text{O}$	Kolwezite	$(\text{Cu}, \text{Co})_2(\text{CO}_3)(\text{OH})_2$
Libethenite	$\text{Cu}_2(\text{OH})\text{PO}_4$	Stainierite	$\text{Co}_2\text{O}_3 \cdot \text{H}_2\text{O}$
Pseudomalachite	$\text{Cu}_2(\text{OH})_4\text{PO}_4\text{H}_2\text{O}$	Amorphous heterogenite	$\text{CoO} \cdot 2\text{Co}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$
Tenorite	$\text{CuO}$		

In the Katanga province of the DRC, cobalt is commonly produced from heterogenite ( $\text{CoO} \cdot 2\text{Co}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$ ) as a by-product of copper production. Cobalt in heterogenite occurs in both the 2+ and 3+ oxidation states. In contrast to copper oxide minerals, which readily dissolve in sulphuric acid solution, cobalt is difficult to leach from heterogenite. This is because when heterogenite is leached in an inorganic acid such as sulphuric acid,  $\text{Co}^{2+}$  easily goes into solution, but  $\text{Co}^{3+}$  does not dissolve:



The insoluble  $\text{Co}^{3+}$  becomes soluble only after reduction to  $\text{Co}^{2+}$ . Therefore the hydrometallurgical dissolution of  $\text{Co}^{3+}$  can take place only in the presence of a reducing agent. The reducing agents commonly used in the process include ferrous ions (present in the leach solution as a result of leaching of iron minerals in the ore and leaching of iron scrap), sodium metabisulphite ( $\text{Na}_2\text{S}_2\text{O}_5$ ), and hydrogen peroxide (Apua and Mulaba-Bafubiandi, 2011; Lydall and Auchterlonie, 2011; Seoa *et al.*, 2013). The consumption of these reducing agents is generally high and these make up 47% of the total operation which makes the production of copper and cobalt very expensive (Mulaba-Bafubiandi *et al.*, 2007).

The use of sulphuric acid as the main leaching agent also poses a threat to the environment. Sulphuric acid waste leach solution, because it is non-biodegradable and toxic, is stored in on-site holding ponds, which are securely lined. Even though the holding ponds are considered environmentally safe there have been reports of spills impacting groundwater even miles away (Freeman, 2005). Therefore, an economical method of extracting the minerals that uses a more environmentally friendly leaching reagent is required in order for the processing of these low-grade ores to be profitable.

Since inorganic acids have not performed well in economic terms or in meeting the standards for 'green' chemistry and environmental impact, this has prompted the need to consider organic acids as lixivants. To date, organic acids have not been used widely as leachants due to their reported low leaching efficiencies. They are also very expensive and are, as a result, most unlikely to be used on low-grade ores in conventional processing routes. However, they are attractive due to the fact that they have been found to cause less harm to the environment as they are biodegradable. In addition, organic acids are also recyclable

(Gharabaghi *et al.*, 2010). Organic acids extract metals by forming complexes. The more stable the complex the higher the extraction rate, the smaller the ionic radius of the target metal the more stable the complex formed, and the higher the oxidation state of the metal the more stable the metal complex (Weisstein, 2011).

Currently there are no documented studies on the leaching of copper-cobalt oxide ores from the Central African Copperbelt by organic acids. In the present work, preliminary studies have been conducted to establish the feasibility of leaching using an organic acid. The leaching behaviour of a copper-cobalt oxide ore in an organic acid environment (tartaric acid) was compared with that in an inorganic environment (sulphuric acid) fortified with a reducing agent (hydrogen peroxide). Tartaric acid has been observed to chelate metal ions and is relatively cheap compared to other organic acids. This choice was further reinforced by studies comparing the leaching rates of heavy metals from contaminated soils and spent batteries using different organic acids, which showed that tartaric acid and citric acid could remove heavy metals from contaminated soils and waste material more efficiently and rapidly than all other potential organic extractants (Wasay *et al.*, 2001; Li *et al.*, 2010).

### Materials and methods

#### Ore sample

The ore used in the test work is a copper-cobalt oxide ore from the Katanga Province in the DRC. The ore was crushed and milled to 80% -150  $\mu\text{m}$ . The composition of the ore is given in Table II.

#### Reagents

The main reagents included analytical grade sulphuric acid (98%) as a leaching reagent, analytical grade hydrogen

Table II

**Chemical composition of the Cu-Co ore sample used in the test work**

Element	Cu	Co	Zn	Ni	Fe	Mn	Mg	SiO <sub>2</sub>
Wt%	4.53	0.3	0.029	0.003	1.4	0.22	2.48	84.5

## Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

peroxide (30%) as the reducing agent, 100% tartaric acid, and distilled water for dilution. All reagents were sourced from Merck Millipore.

### Experimental method

#### Inorganic acid leaching

Dilute solutions of sulphuric acid and hydrogen peroxide were prepared separately. The dilute solutions were mixed in beakers accordingly to obtain the desired pH. The beakers were then placed in a shaking water bath that was set at the desired temperature and the solutions were given time to reach a steady temperature. The pH of the solutions was monitored using a calibrated pH meter and the temperature was measured using a thermometer.

Once the solution pH and temperature of the solution were stable, the ore sample was introduced into the solution in the beakers. The pulp in the beaker was continuously stirred for 3 hours to facilitate leaching. Table III summarizes the test conditions for the inorganic acid leaching tests.

The experiments were all undertaken over a 3 hour period.

#### Organic acid leaching

Dilute acid solutions of different concentrations were prepared by dissolving tartaric acid powder in distilled water. The pH of the solutions was measured. The solutions were poured into beakers and the beakers were placed in a shaking water bath to achieve the desired temperature. Once the leaching solution in the beaker reached a steady temperature, the ore sample was introduced. The pulp was left to leach for 24 hours while being continuously stirred. A sample for analysis was taken after the first 3 hours.

Table IV summarizes the test conditions for the organic acid leaching tests.

The experiments were all undertaken over a 3 hour period.

#### Leachate analysis

Leachate samples were analysed to determine the concen-

tration of copper and cobalt after each experiment. In both sets of experiments, the leached pulp was left to settle in order to allow for solid/liquid separation to occur. The pulp was then filtered using filter paper, a Büchner funnel, and a filter flask to obtain the leach solution. Samples of the filtered solution were poured into sample bottles and sent for copper and cobalt analysis by inductively coupled plasma mass spectrometry (ICP-MS) using a Perkin Elmer Nexlon 300D instrument.

### Results and discussion

#### Inorganic acid leaching

##### Effect of sulphuric acid concentration

Figure 1 shows the extraction of the metals as a function of sulphuric acid concentration. The results show similar trends for the extraction of both copper and cobalt. At 0.4 M acid concentration, cobalt and copper extractions were 34.0% and 35.0% respectively. Extraction increased to a maximum of 97.4% (Cu) and 78.2% (Co) at 0.8 M sulphuric acid concentration, and then declined with further increases in acid concentration to 78.3% for copper and 63.3% for cobalt at 1.2 M.

One would expect that with an increasing acid concentration the dissolution of the copper and cobalt would

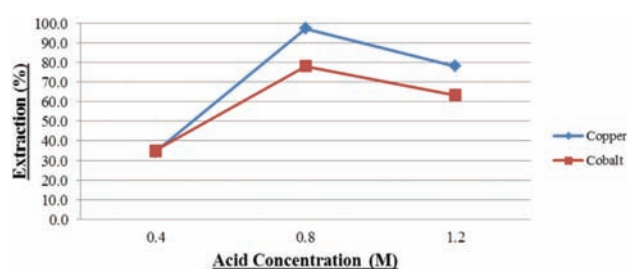


Figure 1 – Effect of sulphuric acid concentration on copper and cobalt extraction (temperature 25°C, hydrogen peroxide concentration 3M, leaching time 3 hours)

Table III

#### Test conditions for inorganic acid leaching in a reducing environment

Test	Temperature (°C)	Sulphuric acid concentration (M)	Hydrogen peroxide concentration (M)
Effect of sulphuric acid concentration	25	0.4, 0.8, 1.2	3.0
Effect of hydrogen peroxide (reducing agent) concentration	25	0.4	4.0, 5.5, 6.5
Effect of temperature	20, 30, 40	0.8	4.0

Table IV

#### Test conditions for inorganic acid leaching

Test	Temperature (°C)	Tartaric acid concentration (M)	Hydrogen peroxide concentration (M)
Effect of tartaric acid concentration	25	0.15, 0.25, 0.35	0.0
Effect of hydrogen peroxide (reducing agent) concentration	25	0.35	3.0, 4.5, 5.5, 6.5
Effect of temperature	20, 30, 40, 50	0.35	0.0

## Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

increase, as there are more H<sup>+</sup> ions available. However, this is not the case. The Eh-pH diagrams for copper and cobalt in Figure 2 and Figure 3 show that copper and cobalt ionization is favoured at relatively low pH levels. The diagrams indicate that in order to solubilize copper as Cu<sup>2+</sup>, the copper oxide minerals have to be leached in highly acidic conditions (pH <1). At pH conditions >1, a solid CuOFeO<sub>2</sub> is formed (Figure 2).

Similarly, cobalt is best leached at pH <1. At pH levels >1, a solid CoO·Fe<sub>2</sub>O<sub>3</sub> is formed, as seen in Figure 3, which has a passivating effect on the leaching of cobalt.

Thus as the pH increases beyond about 2 there is a possibility of formation of solid compounds of copper (CuFeO<sub>2</sub>) and cobalt (CoO·Fe<sub>2</sub>O<sub>3</sub>). These solids have a passivating effect on the leaching reactions, resulting in a decrease in the dissolution of both copper and cobalt. Solutions >1.0 M in concentration had a starting pH greater than 1. Addition of ore may have increased the pH to levels that favour passivation.

The shift from increasing extraction to decreasing extraction (Figure 1) may also be due to a change in the rate-controlling step. At acid concentrations between 0.4 M and 0.8 M, the reaction kinetics may be controlled by the mass transfer of acid from the bulk solution to the particles. At concentrations from 0.8 M to 1.2 M, the controlling

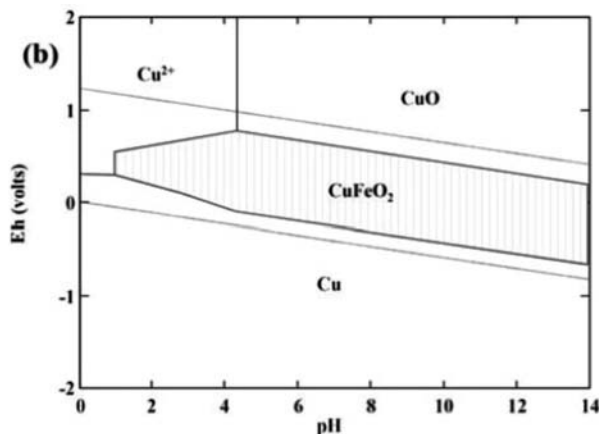


Figure 2—Eh-pH diagram of the Cu-O-Fe system at 25°C (Schlesinger et al., 2011)

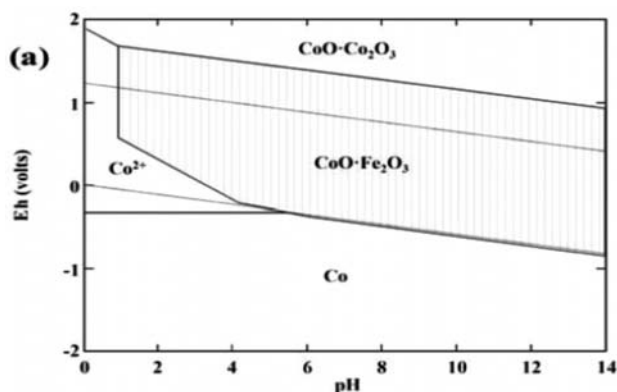
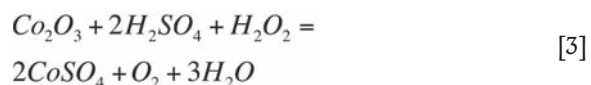
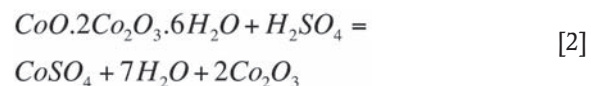


Figure 3—Eh-pH diagram of the Co-O-Fe system at 25°C (Schlesinger et al., 2011)

mechanism may have changed, so that further increases in acid concentration would have no effect in the dissolution of both cobalt and copper ores.

### Effect of the concentration of the reducing agent

The reaction of Co<sup>3+</sup> oxides in the presence of hydrogen peroxide as the reducing agent is expected to proceed by the following reactions:



The effect of a reducing agent on metal recoveries was investigated in preliminary test work that focused on the solution Eh. In the absence of reducing agent the Eh of the solution varied between 600 and 900 mV vs SCE (0.242 V) over the leaching period. However, on addition of about 3.0 M hydrogen peroxide the Eh of the solution decreased drastically to values around 300 to 500 mV vs SCE. According to Figure 1, the lower Eh of the solution subsequently enhances the dissolution of Co (III) phase.

The effect of hydrogen peroxide concentration in conjunction with sulphuric acid was then tested. Figure 4 shows the metal extraction as a function of reducing agent concentration.

The results show similar trends for both copper and cobalt extraction. Maximum extractions of 95.1% for copper and 79.4% for cobalt were obtained at around 4 M hydrogen peroxide. Extraction of copper and cobalt then decreased to 59.3% and 63.8% respectively at about 6.5 M hydrogen peroxide. It is important to note that copper extraction was higher than that of cobalt at all hydrogen peroxide concentrations except 6.5 M. This possible indicates different reaction mechanisms controlling the Cu and Co extraction processes. Another point is the sharp increase in metal extraction from 3.0 M to 4.0 M hydrogen peroxide concentration, which is followed by a decrease in extraction at 5.5 M and above. This clearly indicates that the concentration of reducing agent has a positive effect on metal extraction only up to a certain extent; above this range the reaction rate becomes less dependent on hydrogen peroxide concentration. At reducing agent concentrations above 4 M, the mass transfer of reducing agent from solution to particles may no longer be the rate controlling mechanism.

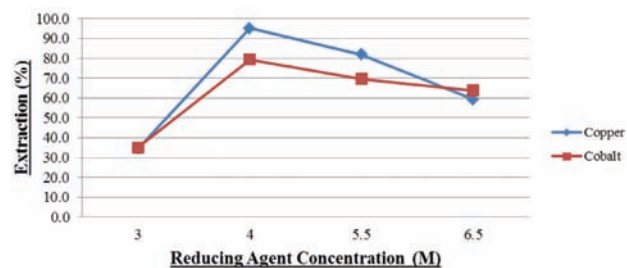


Figure 4—Effect of hydrogen peroxide concentration on copper and cobalt extraction (temperature 25°C, sulphuric acid concentration 0.4 M, leaching time 3 hours)

## Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

### Effect of temperature

Since the optimum cobalt and copper extractions were obtained with 4.0 M hydrogen peroxide and 0.4 M sulphuric acid, these conditions were used in the temperature tests. Figure 5 shows the metal extractions as a function of temperature. There is a marginal increase in the extraction of both copper and cobalt as the leaching temperature is increased. It is known from the Arrhenius equation that an increase in temperature generally enhances reaction kinetics. Increasing temperature may thus increase the mass transfer kinetics of acid and reducing agent from solution to particles. The reaction at the surface of the particles is also enhanced by increasing temperature, thus leading to increased metal dissolution and higher extraction efficiency.

However, the temperature increase does not seem to have as great an effect on the extraction efficiency of copper and cobalt as compared to acid and reducing agent concentration. The temperature effect was therefore capped at 40°C.

### Organic acid leaching

#### Effect of tartaric acid concentration

Figure 6 shows the extraction of copper and cobalt as a function of tartaric acid concentration.

The copper and cobalt extractions are both much lower than those achieved with the inorganic acid (Figure 1), with the difference being more significant for copper than for cobalt. The maximum copper extracted within the range of tartaric acid concentration used was about 5% at 0.35 M, compared to about 90% in sulphuric acid media. The maximum cobalt extracted was about 38% in tartaric acid compared to about 80% in sulphuric acid media. The dissolution of copper and cobalt is governed by the extent to which the two acids dissociate, which is quantified by their respective dissociation constants (pKa). The lower the pKa value, the higher the dissociation rate. Sulphuric acid has a pKa of 1.99, compared with the pKa<sub>1</sub> of 2.98 and pKa<sub>2</sub> of 4.34 for tartaric acid at 25°C (Murthy, 2008). It is also noticeable from Figure 6 that the maximum leaching ability of tartaric acid was not reached within the selected concentration range. The effect of increased tartaric acid concentrations on cobalt extraction should be investigated in future studies.

Cobalt extraction was much higher than that of copper at all acid concentrations tested. This is notably the reverse of what was observed with the sulphuric acid leaching process,

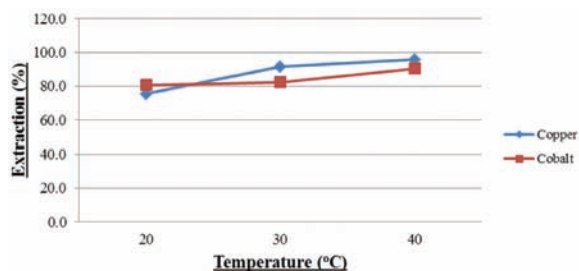


Figure 5—Effect of temperature on copper and cobalt dissolution. Sulphuric acid concentration 0.4 M, hydrogen peroxide concentration 4 M, leaching time 3 hours

where the extraction of copper was significantly higher than that of cobalt. Furthermore, the level of copper extraction did not change significantly with increasing acid concentration. These observations indicate that the cobalt mineral has a faster reaction rate with the organic acid than the copper mineral, and that the leaching reactions of the two metal systems may be controlled by two different mechanisms.

Extraction of metals from ores by organic acids generally takes place through protonation, chelation, and ligand exchange reactions. Thus the organic acid supplies both protons and metal-complexing organic acid anions, with the protons contributing to proton-promoted mineral dissolution. The major factor with organic acids, however, may be that metal-organic complexes can form at the solid-solution interface, weakening cation-oxygen bonds and catalysing the dissolution reaction. The greater the stability of the metal complex formed, the higher the metal dissolution. The stability of the complex depends on the ionic radius and the oxidation state of the metal ion. A smaller ionic radius and a higher oxidation state both increase the stability of the metal complex formed.

Unlike Co (II) complexes, Co (III) complexes undergo ligand substitution reactions relatively slowly and so tend to be stable to ligand exchange (Kim *et al.*, 1993). This could explain the lower cobalt extraction in the organic acid as compared to sulphuric acid enhanced with a reducing agent. This might indicate that the Co (II) mineral species undergo dissolution through the protonation mechanism. The resulting Co (III) species, however, did not undergo much dissolution due to the slow ligand exchange reactions. In view of the low extractions observed with tartaric acid, the effect of additions of a reducing agent was investigated.

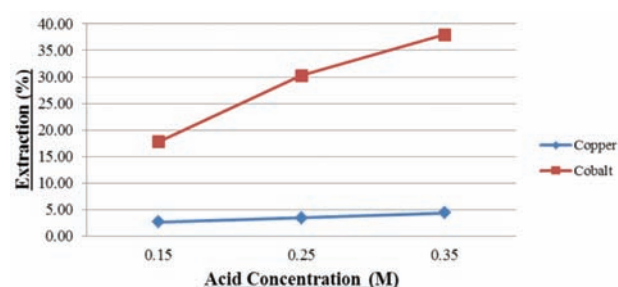


Figure 6—Effect of tartaric acid concentration on copper and cobalt extraction (temperature 25°C, leaching time 3 hours)

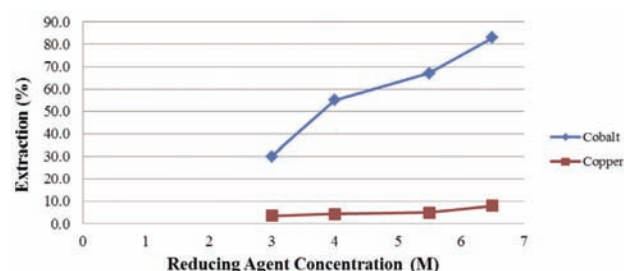
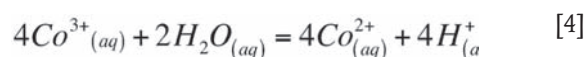


Figure 7—Effect of reducing agent concentration on copper and cobalt extraction (tartaric acid concentration 0.35 M, temperature 25°C, leaching time 3 hours)

## Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

### Effect of addition of a reducing agent

Figure 7 shows the effect of hydrogen peroxide additions to the organic acid leach solution. The addition of a reducing agent had a significant effect on cobalt extraction, but little effect on copper. As outlined in the preceding section it is possible that the addition of a reducing agent will reduce the Co (III) species to Co (II). Furthermore, the uncomplexed Co (III) ion itself is not stable in water due to the hydrolysis/reduction reaction:



The generated Co (II) ions undergo ligand substitution much faster, and as a result cobalt dissolution will be greatly enhanced.

### Effect of temperature

Figure 8 shows the effect of temperature on the extraction of cobalt and copper in tartaric acid in the absence of hydrogen peroxide. Tests were carried out from 20°C to 50°C over a 3 hour leaching period.

As with all chemical reactions, the extraction of both cobalt and copper increases with increasing temperature. Figure 8 shows that in general, an increase in temperature has a much more positive effect on the extraction of cobalt than that of copper. The highest cobalt extraction (62%) was recorded at the highest temperature used (50°C), while only 10% copper extraction was recorded at the same temperature. According to Shabani *et al.* (2012) the dissolution of cobalt is highly dependent on temperature, with the effect being more noticeable in the presence of tartaric acid than in sulphuric acid (Figure 5). Organic acids are weak acids and their metal dissolution abilities are affected by the extent of dissociation. The more the acid dissociates, the greater its ability to solubilize metals. An increase in temperature results in increased dissociation of tartaric acid, increasing the number of hydrogen and ligand ions in the acid and thus enhancing the cobalt extraction.

One other noteworthy aspect is that the temperature tests were carried out in the absence of a reducing agent. It is possible therefore that an increase in temperature beyond 50°C could result in the extraction efficiency for cobalt reaching similar levels to those observed at lower temperatures in the presence of hydrogen peroxide. This aspect should be investigated further in future work, as it could have an impact on the potential applicability and economics of the process.

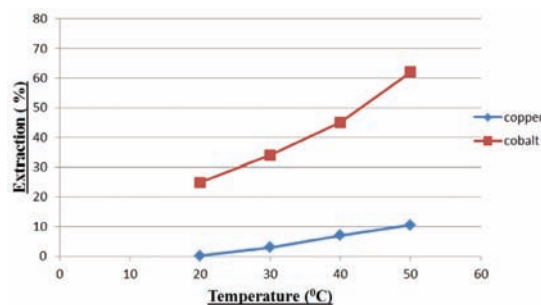


Figure 8—Effect of temperature on copper and cobalt extraction (tartaric acid concentration 0.35 M, leaching time 3 hours)

### Conclusions

Sulphuric acid in the presence of hydrogen peroxide as a reducing agent was able to extract a large amount of both copper and cobalt. About 95% copper and 80% cobalt extractions were achieved in 0.4 M sulphuric acid and 4 M hydrogen peroxide in 3 hours' leaching time at 25°C. Extractions of both copper and cobalt increased with an increase in sulphuric acid concentration up to 0.8 M. Addition of hydrogen peroxide to the sulphuric acid leaching solution had a positive effect on both copper and cobalt dissolution up to 4 M hydrogen peroxide. An increase in temperature, however, did not have as significant an effect on the extraction efficiency of copper and cobalt as the reducing agent concentration.

With tartaric acid as the lixiviant, about 40% cobalt and 5% copper extraction were realized at 25°C. Thus more copper and cobalt were extracted in the inorganic acid environment than in the organic acid environment. However, the addition of hydrogen peroxide to the tartaric acid leaching solution resulted in an 80% cobalt extraction and about 10% copper extraction under the same temperature conditions. In the tartaric acid leaching environment, the change in temperature had a much more pronounced effect on cobalt extraction than that of copper, with about 60% cobalt and 10% cobalt extracted in the absence of hydrogen peroxide. In addition, changes in temperature had a more significant effect on the extraction of cobalt in organic solutions than in the inorganic environment.

The results obtained in these two leaching environments indicate the potential of tartaric acid to extract cobalt, rather than copper, from the copper-cobalt ores. It is recommended that further investigations be carried out with higher concentrations of tartaric acid, since in the current test work the concentration of tartaric acid was too low to achieve maximum leaching capability. Tests involving other commonly used organic acids such as citric and oxalic acid would also add value to this research area.

### Acknowledgements

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### References

- APUA, M. and MULABA-BAFUBIANDI, A. 2011. Dissolution of oxidised Co-Cu ores using hydrochloric acid in the presence of ferrous chloride. *International Journal of Chemical and Biological Engineering*, 28 April. pp. 47–51.
- CRUNDWELL, F.K., MOATS, M., RAMACHANDRAN, V., ROBINSON, T., and DAVENPORT, W.G. 2011. *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*. Elsevier, Amsterdam.
- FREEMAN, N.F. 2005. ADEQ. <http://www.savethesantacruzquifer.info/index.htm> [Accessed 13 October 2013].
- GHARABAGHI, M., IRANNAJAD, M., and NOAPARAST, M. 2010. A review of the beneficiation of calcareous phosphate ores using organic acid leaching. *Hydrometallurgy*, vol. 103. pp. 96–107
- KIM, J.H., BRITTON, J., and CHIN, J. 1993. Kinetics and mechanism of Cobalt(III) complex catalysed hydration of nitriles. *Journal of the American Chemical Society*, vol. 115. pp. 3618–3622.

## Comparing the extent of the dissolution of copper-cobalt ores from the DRC Region

- LI, L., GE, J., WU, F., CHEN, R., CHEN, S., and WU, B. 2010. Recovery of cobalt and lithium from spent lithium ion batteries using organic citric acid as leachant. *Journal of Hazardous Materials*, vol. 176. pp. 288–293.
- LYDALL, M.I. and AUCHTERLONIE, A. 2011. The Democratic Republic of Congo and Zambia: a growing global 'hotspot' for copper-cobalt mineral investment and exploitation. 6th Southern Africa Base Metals Conference, Phalaborwa, 18–20 July 2011. Southern African Institute of Mining and Metallurgy, Johannesburg. pp. 25–38.
- MILLER, G. 2009. Design of copper-cobalt hydrometallurgical circuits. ALTA Nickel-Cobalt Conference (ALTA 2009), Perth, WA.
- MULABA-BAFUBIANDI, A.F., NDALAMO, J., and MAMBA, B. 2007. Microwave-assisted sulphur dioxide flushed acid leaching of mixed cobalt copper oxidised ores. 4th Southern African Base Metals Conference, Swakopmund, Namibia, 23–25 July 2007. *Southern African Institute of Mining and Metallurgy*, Johannesburg. pp. 9–27.
- MURTHY, C.P., ALI, S.F.M., DUBEY, P.K., and ASHOK, D. 2008. University Chemistry. vol. 2. New Age International Publishers, New Delhi, India.
- PRASAD, M.S. 1989. Production of copper and cobalt at Gecamines, Zaire. *Minerals Engineering*, vol. 2, no. 4. pp. 521–541.
- SHABANI, M.A., IRANNAJAD, M., and AZADMEHR, A.R. 2012. Investigation on leaching of malachite by citric acid. *International Journal of Minerals, Metallurgy and Materials*, vol. 19, no. 9. pp. 782–786.
- SCHLESINGER, M.E., KING, M.J., SOLE, K.C., and DAVENPORT, W.G. 2011. Extractive Metallurgy of Copper. 5th edn. Elsevier, Amsterdam. pp. 282–283
- SEO, S.Y., CHOI, W.S., KIMA, M.J., and TRANA, T. 2013. Leaching of a Cu-Co ore from Congo using sulphuric acid-hydrogen peroxide leachants. *Journal of Mining and Metallurgy*, Section B: Metallurgy, vol. 49, no. 1. pp. 1–7.
- WASAY, S.A., BARRINGTON, S., and TOKUNAGA S. 2001. Organic acids for the in-situ remediation of soils polluted by heavy metals: soil flushing in columns. *Water Air Soil Pollution*, vol. 127. pp. 301–314.
- WEISSTEIN, E. Complex ion stability. Weisstein's World of Chemistry. <http://scienceworld.wolfram.com/chemistry/ComplexIonStability.html> [Accessed 23 October 2013]. ♦

## SAIMM 120th Anniversary



The Southern African Institute of Mining and Metallurgy (SAIMM) has redesigned our logo to coincide with our 120th Anniversary. This logo is more aligned with the changes over the last two decades, while maintaining the professionalism that the SAIMM is renowned for. We have also emphasized the fact that we are 120 years old, and have continued to maintain our technical excellence with regard to our Journal and the events that we organize. To add to these achievements we continue to increase our membership.

### The Parts of an Achievement of Arms and their Significance

The arms under consideration comprise separate parts, viz., Shield, Helm, Mantling, Crest, Supporters, Compartment, and Motto.

**The Shield:** This is in blue divided by a golden chevron, to represent the major sections of the industry. The flaming crucibles in the upper section represent Metallurgy and the crossed pick and shovel in the lower section represent Mining.

**The Helm:** This is an Esquire's Helmet, which is the customary type of use for the arms of corporate bodies.

**The Wreath and the Mantling:** These are always in the two main 'colours' of the shield, in this case gold as a metal and blue as the colour. The mantling was originally a short cloak draped from the helmet as a protection against the sun, and the wreath helped to hold the crest in place.

**The Crest:** This served as an additional mark of distinction. In this case the demi-lion represents strength and holds the national flower of South Africa in his left Claw.

**The Supporters:** In this case heraldic beasts have been chosen, symbols of these ancient professions, the black lion representing mining and the golden dragon representing metallurgy. The 'different' marks on their shoulders are carried over from the shield of the Chemical, Mining and Metallurgical Society, and their colours and the diamonds in their collars are intended to represent the main fields of mining in South Africa, namely gold, coal, and diamonds.

**The Compartments:** This is, appropriately, an outcrop of rock.

**The Motto:** 'Capaci Occasio' has been taken over from the Institute's predecessor, the Chemical, Mining and Metallurgical Society, with the exhortation, 'to the capable the opportunity'.

