

Direct cobalt electrowinning as an alternative to intermediate cobalt mixed hydroxide product

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Cobalt (Co) is typically associated with copper and nickel ores and is often recovered as an intermediate hydroxide or carbonate product, which is sold to cobalt refineries to produce London Metal Exchange (LME) quality cobalt metal. The cobalt content of the intermediate hydroxide product is typically 17% (m/m) when lime or limestone is used as precipitant and 35% to 40% (m/m) when MgO is used as precipitant. Because of the drive towards producing higher value products domestically, a new alternative process flow sheet for cobalt recovery by means of electrowinning was considered. A number of potential flow sheets were developed for 'direct' cobalt electrowinning. These flow sheets were compared to the typical cobalt precipitation flow sheet with regard to reagent consumption, transport costs, and energy costs.

Laboratory electrowinning tests were conducted to determine current efficiency and power consumption that could be expected for some of the 'direct' cobalt electrowinning flow sheet options evaluated. These results and their potential impact on operating costs and value of the cobalt product are detailed in this paper.

Introduction

Cobalt (Co) is a high-value base metal that typically occurs in copper (Cu) and nickel (Ni) ores at relatively low concentrations; hence, it is usually produced at low tonnages as a by-product of Cu and Ni. The largest Co reserves and producers are located on the Copperbelt in the Democratic Republic of Congo (DRC) and Zambia. Other important producers include Australia, Brazil, Cuba, Russia, and China. The Co reserves in the DRC were estimated to be 45% of the total world reserves, and the DRC produced 53% of the world's Co in 2011 (Bedder, 2013).

A 2012 KPMG report on the DRC revealed that Co accounted for 39% of total DRC exports, second only to Cu (43% of exports). However, only 5% of the Co exported was refined, with the remainder being Co concentrate and intermediate product, which usually is a mixed hydroxide precipitate (MHP) (Parant *et.al.*, 2013). This is an undesirable situation, as only minimum returns for one of the country's major export products are being realized. In an effort to promote the expansion of exporting domestically value-added products, the DRC government reaffirmed its ban on the export of Cu and Co ores and concentrates in May 2013. However, the inconsistent domestic electricity supply in the DRC is a concern for domestic Co refining. Poor transport infrastructure is a major issue in the DRC, and import costs of capital goods for the expanding mining industry continue to increase. Furthermore, the DRC was rated 'upper-moderate' by the NKC Political Risk Rating (Parant *et.al.*, 2013). Capital investment required for Co refining to LME grade metal is high and the unfavourable business and political climate in the DRC renders such investment risky. However, these challenges present an opportunity for technology development to produce improved quality Co products, hence higher value, at lower capital (capex) and operating costs (opex).

Direct Co electrowinning (EW) from a dilute Cu solvent extraction (SX) raffinate in a typical Cu-Co flow sheet is proposed as an alternative to the precipitation of a MHP product. Although Co metal produced by direct EW would not be LME grade, its revenue is projected to be significantly higher than that of MHP, and this is the major economic driver of the proposed flow sheet. This study aims to compare Co revenue and preliminary opex for the basic Cu-Co flow sheet producing MHP to the direct Co EW flow sheet based on reagents, transportation costs, and cobalt losses.

Background

Cobalt production

There are generally three major Co products from Cu-Co ores, namely: Co concentrate, intermediate Co precipitates, and LME grade Co metal. A typical Cu-Co flow sheet for producing MHP using MgO as the precipitant is illustrated in

Figure 1, with various process options for alternative Co products shown in dotted lines (Pawlik and Lydall, 2012). This flow sheet was used as a base case to which the alternative 'direct' Co EW flow sheets were compared.

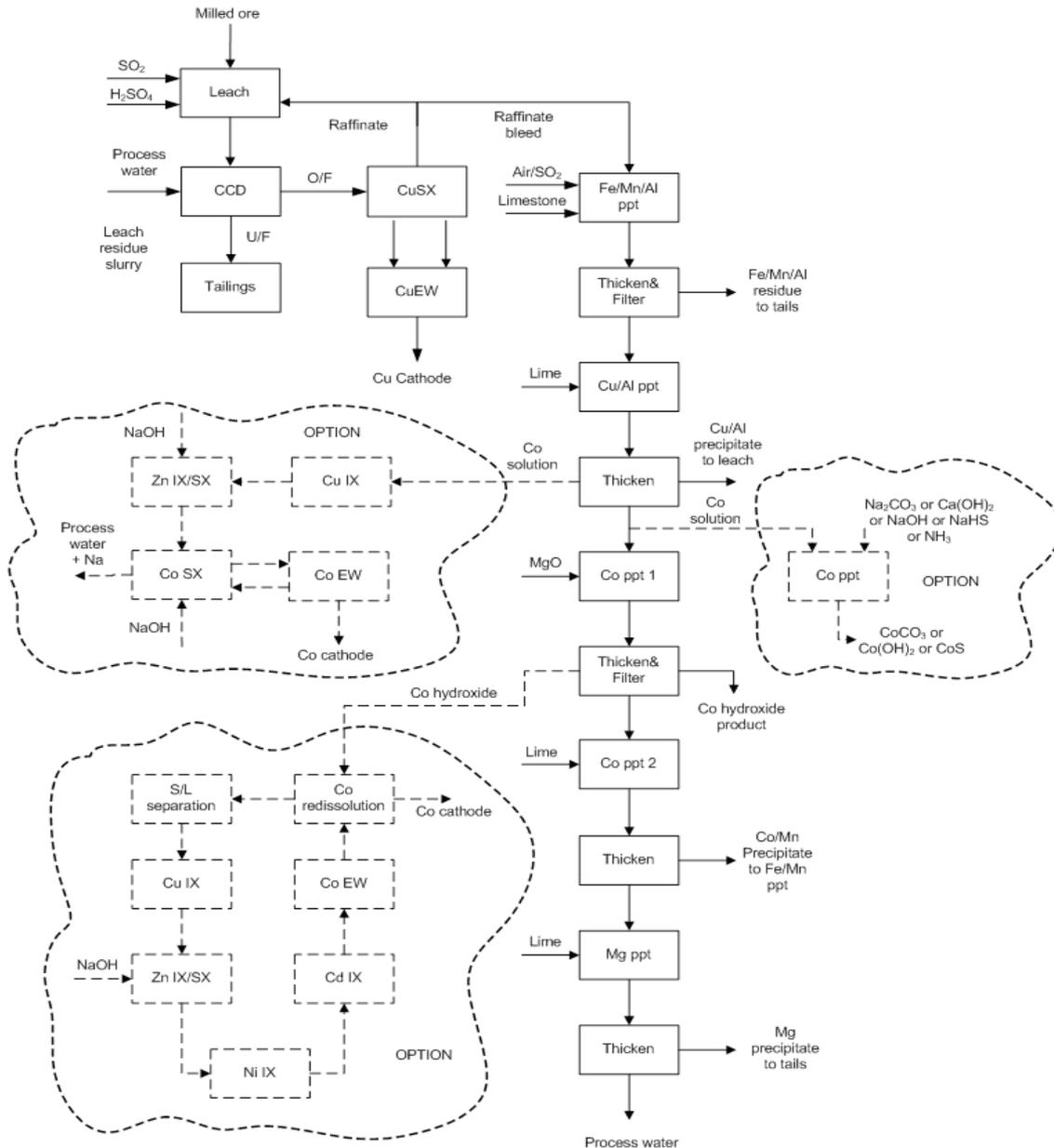


Figure 1. Typical copper-cobalt flow sheet for producing MHP (Pawlik and Lydall, 2012)

MHP is the common intermediate Co product for the Copperbelt. Other intermediates can be in the form of carbonates, sulphides, or sulphates. MHP normally contains 17% (m/m) Co when lime or limestone is used as precipitant and 35 to 40% (m/m) when MgO is used as precipitant. The import and transport costs of reagents, coupled with the high transport costs for the relatively low Co content product, might not result in optimum returns, as premium quality MHP is sold at approximately 60% of the price of LME grade Co. The risk associated with capital investment has to be taken into account as well.

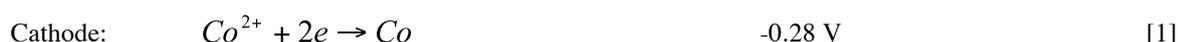
The highest revenue is generally obtained for LME grade Co metal, containing a minimum of 99.3% (m/m) Co. Two options for producing LME grade Co are also shown in Figure 1, namely:

- From the raffinate after purification and upgrading via ion exchange (IX) and SX
- By refining the MHP product, which also involves IX and/or SX after re-dissolution of the MHP with spent electrolyte.

The capex and opex for producing LME grade Co metal for both options are high (Pawlik and Lydall, 2012). Such circuits pose challenges, including relatively high Co losses incurred during impurity removal (precipitation, IX, or SX), and inefficient washing during solid/liquid separation. Furthermore, the stringent impurity removal requirements increase the capex and opex of the refining circuits significantly. As a result, the bulk of Co exported from the DRC is in the form of intermediates.

Cobalt electrowinning

The Co EW process is challenging due to the relatively low reduction potential of Co (Equation [1]) compared to hydrogen (H_2 , Equation [2]), which means that the reduction of H^+ ions is thermodynamically preferred. As a result, the current efficiency for Co EW is lowered by the competing H_2 reaction, which increases with a decrease in pH or increase in acid concentration in the feed. Reduction potentials for Cu (0.34 V) and Ni (-0.25 V) are also more positive, hence reduction of Cu and Ni is thermodynamically more favourable than that of Co, therefore these metals co-deposit with Co, resulting in low current efficiency for Co metal production and impure Co metal. Although reduction potentials for metals such as cadmium (Cd) (-0.4 V), iron (Fe) (-0.45 V), and zinc (Zn) (-0.76 V) are more negative than that of Co, these metals have been known to compete with Co deposition, depending on their concentration in solution (Kongolo *et.al*, 2005). Hence, stringent purification of the Co EW feed electrolyte is required. Co metal is also inherently stressed and prone to peeling from the cathode blank, resulting in short-circuiting between the anode and cathode, consequently reducing the current efficiency. The electrode reactions for Co EW are as follows:



The oxidation of water is the primary anodic reaction; however, Mn will also be oxidized to MnO_2 if present in the feed to EW (Equation [4]). Both anodic reactions would result in acid formation, which promotes H_2 evolution at the cathode (in an undivided cell), and oxidation of Mn^{2+} to form MnO_2 would result in anode sludge formation.

The operating conditions for conventional Co EW in undivided cells are listed in Table I. The delta Co is 5 g/L, which is low compared to the 15 g/L delta Cu used for Cu EW. The primary reason for this is to minimize the acid concentration in the cell and hence the production of H_2 , thereby maximizing the current efficiency. Current efficiency and power consumption typically range between 65 to 90% and 3 - 3.5 k Wh/kg Co, respectively.

Table I. Typical Co EW conditions in undivided cells

Current density, A/m ²	250
Temperature, °C	65
Delta Co, g/L	5
Feed pH	3 - 4
Feed [Co], g/L	50 - 55
Na ₂ SO ₄ , g/L	50
[Mn], g/L	2

The proposed direct EW of Co from the low-grade Cu SX raffinate presents even greater challenges due to the low Co concentration and increased impurity levels. Hence, it was expected that the current efficiency and power consumption for direct Co EW would be considerably poorer than those of conventional Co EW circuits, but the overall economic feasibility of the process would determine the final commercial potential and value of the direct EW technology.

Current efficiency is affected by electrolyte pH, metal concentration, impurity levels, and applied current density. The following aspects have to be considered during the design of the EW circuit:

- Current efficiency increases with an increase in electrolyte pH and Co concentration. The high pH is due to reduced H^+ concentration; however, pH increase is limited by precipitation of metal hydroxides. The optimum pH range is 3-4 (Sharma *et.al*, 2005)
- Increasing current density has a slight positive effect on Co EW current efficiency up to a maximum, and the increase is restricted by the Co mass transfer across the Nernst diffusion layer on the cathode. As the applied

current density increases, the metal deposition rate increases and becomes faster than the rate at which metal ions are supplied to the cathode surface; hence, metal deposition becomes mass-transfer limited and H₂ evolution increases. High current densities also promote dendritic growth, which, if not controlled, may result in short-circuiting between the electrodes and hence a reduction in current efficiency. Rough Co deposits also result in poor metal purity due to entrainment of electrolyte during deposition

- The flux of the electrolyte at the cathode surface must be optimal to maximize current efficiency for Co EW under mass transfer limitations. Additional agitation might be considered in order to enhance the Co mass transfer, but the capex and opex for this have to be included in a trade-off study
- The external circuit also affects current efficiency; e.g stray currents resulting from electrical leakages.

Power consumption is directly proportional to cell voltage and inversely proportional to current efficiency. A balance must be maintained between maximizing metal production by increasing current density, while minimizing power consumption. Cell voltage is affected primarily by the applied current density, electrode material, electrical contacts, electrode spacing, and electrolyte conductivity. The latter is generally the most practical variable to optimize, as current density and inter-electrode spacing are effectively fixed for existing plants. Alkali metals such as sodium (Na), potassium (K), and magnesium (Mg) may be used to increase electrolyte conductivity (Sharma *et.al*, 2005). Sodium sulphate (Na₂SO₄) is typically used in conventional Co EW. For new plants, the design has to be optimized in order to minimize costs, while taking operational simplicity into account.

Competing electrowinning technology

The EMEW electrowinning technology, designed by Electrometals Technologies Ltd., is a direct competitor to the direct Co EW technology. The EMEW cells have the advantages of high mass transfer which improves current efficiency, high current densities, small plant footprint, powder production (no risk of Co metal peeling away from cathode blank), and high metal extraction (Weight, 2011). There are a number of drawbacks to this technology:

- Very high fluxes are employed in order to enhance the current efficiency. This would increase the capex and opex significantly
- Powder production from the low-grade Co solution investigated during this study would not be preferred, due to the presence of Mn. Manganese would form anode sludge and report to the Co powder, thereby resulting in a lower purity Co product. Solid/liquid separation and drying of the Co powder would incur additional capex and opex
- DSA anodes, coated with precious metals, are used in EMEW cells, and this incurs higher capex and opex
- Two small-scale Co EMEW plants have been installed, but neither was successful (Weight, 2011).

Experimental procedure

Synthetic sulphate solutions were used to conduct laboratory and pilot-scale EW tests to determine process parameters for Co EW from dilute Co sulphate solutions. The feed compositions of the synthetic solutions (Table II) were based on results from the process simulations performed for the base case flow sheet (discussed later). However, the Zn concentration was increased from 1.4 mg/L achieved for the specific ore used for the simulations to 10 mg/L in order to represent a wider range of ores. The pH of the synthetic feed solution was adjusted to 3.5 by addition of concentrated sulphuric acid (98% (w/w)). Sodium saccharin and thiourea were added to the feed at 50 mg/L and 3 mg/L respectively.

Table II. Co electrowinning feed compositions

Metal concentration, mg/L							
Cu	Ni	Co	Zn	Mn	Mg	K	Ca
10-50	40 - 190	3500	10 - 30	200	1600 – 12000	1510	500

Laboratory-scale tests

An undivided polypropylene EW cell with a solution volume of 3.7 L was used. Two Pb-Ag (1% Ag) alloy anodes and one sandblasted 316 stainless steel cathode blank were used at 45 mm anode-to-cathode spacing. The cathode blank dimensions were 0.105 m × 0.15 m (0.0315 m² total area, both sides). Direct current (DC) was supplied to the electrodes by a rectifier at the specified current density. The cell electrolyte temperature was maintained at 65°C by pumping it through a heat exchange rat a recirculation flux of 3.1 m/h. The spent electrolyte was collected in a discharge tank without recycling.

Pilot-scale tests

The pilot test set-up was similar to the laboratory set-up. The cathode plating area was 0.62 m² (1.36 m × 0.225 m × 2), the solution volume in the cell and recirculation pipes was 80 L, and the anode-to-cathode spacing was 80 mm. The electrolyte recirculation flux was 22.7 m/h on the pilot scale (which was the maximum flow meter setting). The cell electrolyte temperature was maintained at 65°C by pumping it through a heat exchanger. The spent electrolyte was collected in a discharge tank without recycling.

Results and discussion

Cobalt electrowinning laboratory tests

Numerous laboratory-scale tests were conducted in order to determine the optimum conditions for Co EW from dilute solutions. The following parameters were tested during the laboratory tests:

- Current density
- Solution conductivity (by varying magnesium sulphate concentration in the feed)
- Electrolyte flux
- Cu, Ni, and Zn concentrations (as impurities in Co metal)
- Effect of Mn (formation of anode sludge).

Current density

The laboratory tests conducted at different current densities are listed in Table III. Current density was varied by adjusting the direct current applied to the electrodes for the specific cathode area. The effect of current density was evaluated for a delta Co of 1.5 g/L. Hence, the feed flow rate had to be varied for the different current densities in order to achieve the delta Co of 1.5 g/L. This was done in an attempt to evaluate the effect of current density only, and exclude the effect that an increase in acid concentration would have on the performance of the system. The other test conditions were the same, including the solution flux (3.1 m/h), which was set by the solution recirculation rate (through the heat exchanger). The results obtained during these tests are presented in Figure 2 and Figure 3.

Table III. Laboratory tests - various current densities

Test number	Current density	Applied current	Feed flow rate	Duration
	A/m ²	A	L/h	h
1	50	1.6	0.29	72
2	100	3.2	0.58	78
3	125	3.9	0.72	77
4	150	4.7	0.87	76
5	175	5.5	1.01	75
6	200	6.3	1.15	75
7	250	7.9	1.44	74

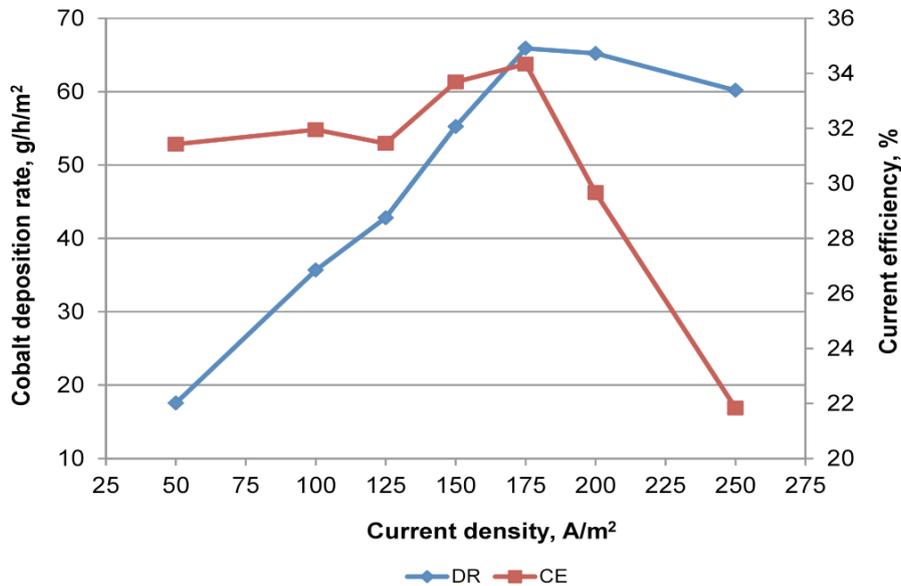


Figure 2. Effect of current density on cobalt deposition rate (DR) and current efficiency (CE)

A sudden decrease in current efficiency was observed at current densities above 175 A/m², which coincided with the maximum Co deposition rate of 66 g/h/m² at 175 A/m² (Figure 5). The decrease in current efficiency above 175 A/m² would have been as a result of a limitation on the rate of Co mass transfer through the Nernst diffusion layer, and hence more H₂ evolution would have occurred. Therefore, 175 A/m² was determined as the optimum current density for direct Co EW at a delta of 1.5 g/L from a feed Co concentration of 3.5 g/L, as there would be no added benefit at higher current densities. Power consumption increased significantly at current densities above 175 A/m² as a result of the decrease in current efficiency and an increase in cell voltage (Figure 3). Although the optimum current density of 175 A/m² would result in a smaller Co EW plant, hence reduced capex, the operating cell voltage and power consumption would result in higher opex compared to lower current densities. An economic trade-off for individual applications would be required, taking into account the financial strategies of different clients.

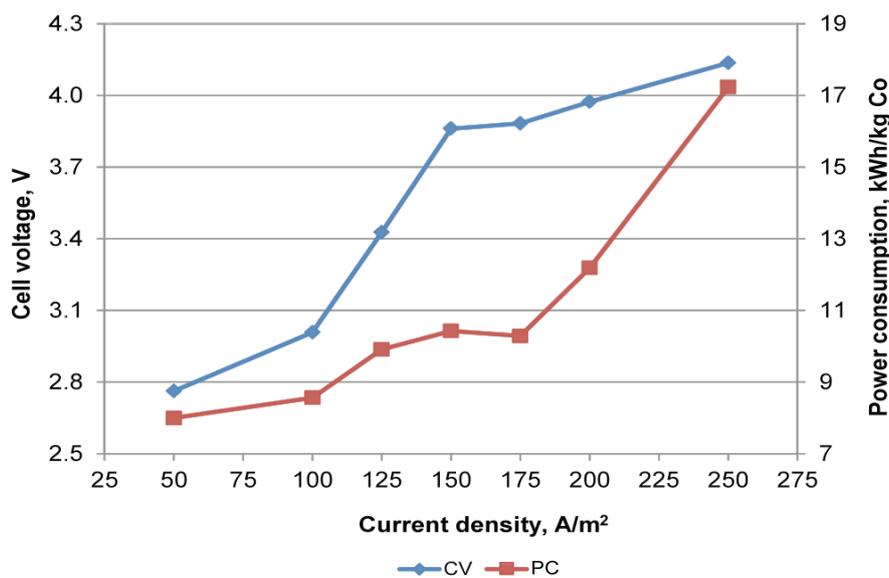


Figure 3. Effect of current density on cell voltage (CV) and power consumption (PC)

Solution conductivity

Improved solution conductivity in conventional Co EW is generally achieved by the addition of Na_2SO_4 . However, for direct Co EW this is unfeasible. Nevertheless, there would be an opportunity to improve the solution conductivity by recycling Mg to build up to higher concentrations. The typical Cu-Co ores on the Copperbelt would provide a Mg concentration of 1-2 g/L when a Co concentration of around 3.5 g/L is targeted in the Cu SX bleed stream.

The effect of electrolyte conductivity was tested by adding magnesium sulphate (MgSO_4) at Mg concentrations of 1.6, 3.8, 5.5, 7.9, and 11.9 g/L. These tests were done at fluxes of 1.2, 1.9, 2.8, and 3.7 m/h. All tests were conducted at a feed flow rate of 0.72 L/h and a current density of 125 A/m^2 for 24 hours. The results are shown in Figures 4 to 6.

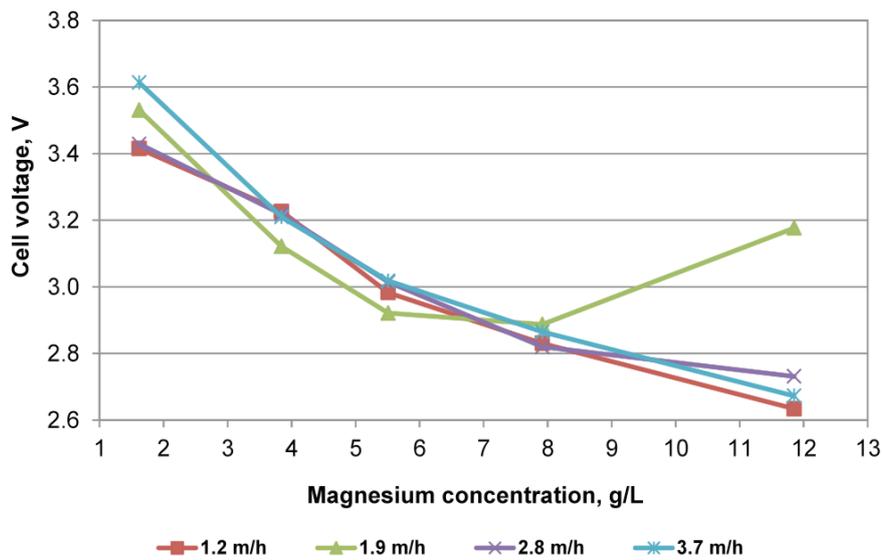


Figure 4. Effect of electrolyte conductivity and flux on cell voltage

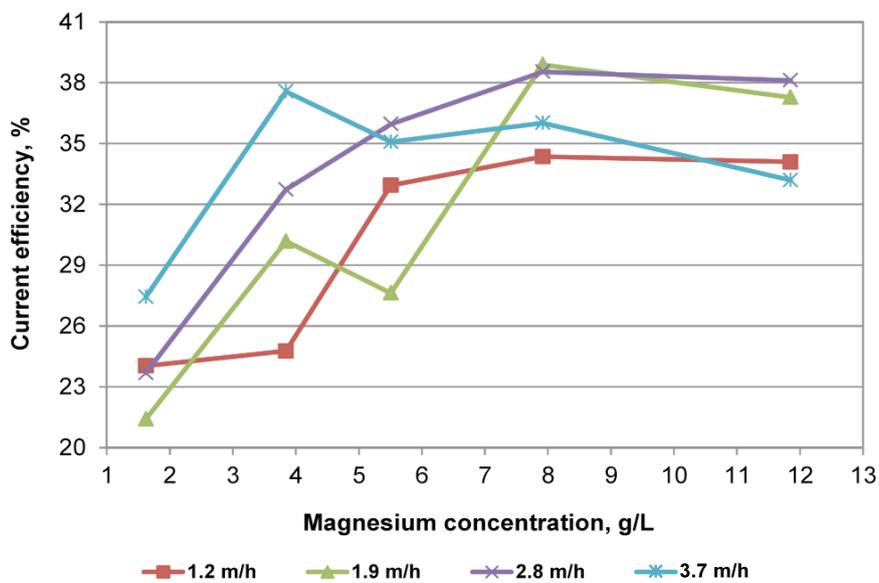


Figure 5. Effect of electrolyte conductivity and flux on current efficiency

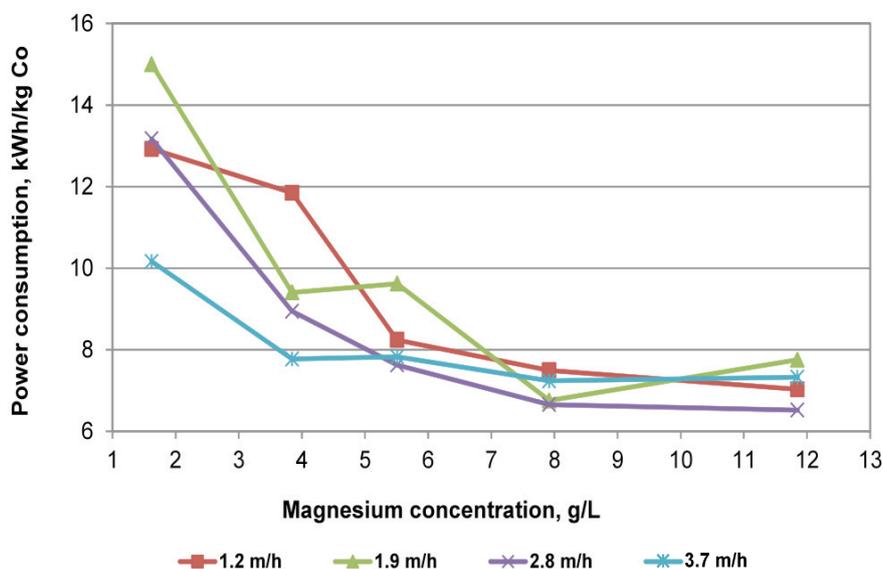


Figure 6. Effect of electrolyte conductivity and flux on power consumption

The following results were obtained:

- As expected, the cell voltage decreased with an increase in Mg concentration due to the increase in electrolyte conductivity (Figure 4)
- Current efficiency increased with increasing Mg concentration and levelled off at 8 g/L Mg (Figure 5). There was a marked improvement in current efficiency when the Mg concentration was increased from 1.6 to 4-5 g/L. Sharma *et.al* (2005) attributed the increase in current efficiency observed when adding Na_2SO_4 during conventional Co EW to the decrease in cell voltage, which resulted in a decreased rate of H_2 evolution, and hence increased current efficiency for Co deposition
- Consequently, power consumption decreased with increasing Mg concentration and the major benefit was observed for an increase in the Mg concentration up to 5 g/L (Figure 6).

Electrolyte flux

An increase in the solution flux across the cathode area from 1.2 m/h to 3.7 m/h (Figures 4-6) resulted in an improvement in power consumption (decreased from 13 to 10 kWh/kg of Co) at Mg concentrations lower than 4-5 g/L. However, at Mg concentrations higher than 5 g/L, the effect of the flux, within the limits tested, was minimal.

Impurity concentrations: Cu, Ni, and Zn

The effects of the concentrations of Cu, Ni, and Zn as impurities in the low-grade Co solution on the performance of the direct Co EW system were investigated in the laboratory tests. The test conditions were 125 A/m^2 current density, 3.1 m/h electrolyte recirculation flux, and 0.72 L/h feed flow rate. Two test Co metal products were produced, one at relatively high and the other at lower impurity concentrations. The impurity levels tested and the results are given in Table IV.

The Co products obtained at the two impurity levels tested are shown in Figure 7. The cell voltages, current efficiencies, power consumptions, and Co metal purities for the two tests are also given in Table IV. The high-impurity deposit was dendritic and the low-impurity deposit was relatively smooth and compact (Figure 7). The purity of the Co metal produced at lower impurity levels in the feed (98.8% Co) was close to the 99.3% Co minimum LME grade specification; hence, the product might generate a higher revenue than that produced at higher impurity levels. This was not taken into account during the present evaluation. Major impurities in both Co metal deposits were $\text{Cu} > \text{Ni} \gg \text{Ca} > \text{S} > \text{Zn}$.

Table IV. Impurity levels tested

Metal	High impurity level		Low impurity level	
	Initial cell electrolyte	Final cell electrolyte	Initial cell electrolyte	Final cell electrolyte
	mg/L			
Cu	50	4.2	10	10
Ni	190	110	40	0
Zn	30	10	10	0
Mn	200	27	180	39
Performance				
Cell voltage, V	2.7		2.7	
Current efficiency, %	36		40	
Power consumption, kWh/kg Co	6.9		6.2	
Co purity, %	93.5		98.8	

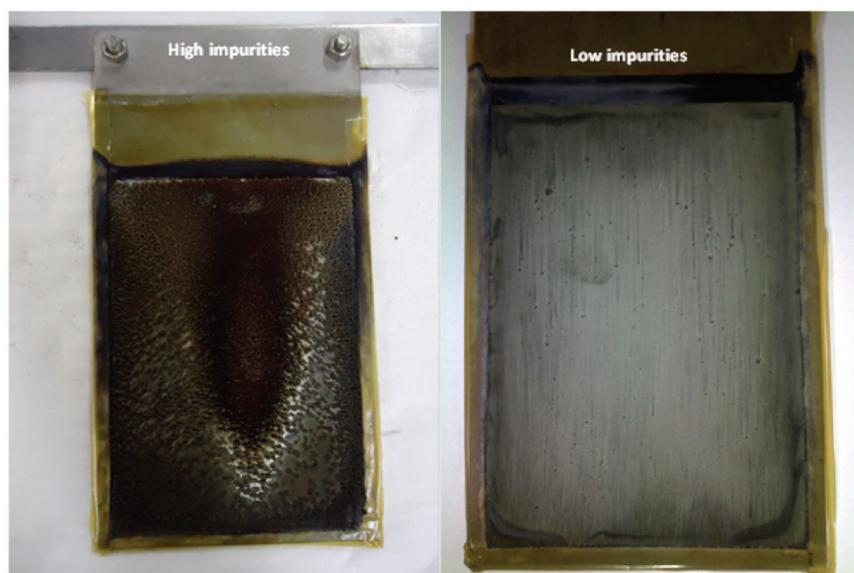


Figure 7. Co deposit for relatively high and low impurity levels

Effect of Mn

Mn in solution was oxidized and resulted in a sludge layer on the anode surface (Figure 8). The chemical composition of a sludge formed at 250 A/m² and 5 L/h feed flow rate is shown in Table V. The major components were MnO (54% (m/m)) and Co (16% (m/m)). An attempt was made to characterize the sludge by X-ray diffraction (XRD) analysis; however, it was amorphous and the phases of Mn and Co could not be determined. Mn and Co most likely oxidized to MnO₂, and Co₂O₃/Co(OH)₂. Anode sludge production rate at 33% current efficiency and 45 g/h/m² deposition rate was 41 kg per ton Co, which translated to a 33 t/a Co loss for a 5000 t/a Co EW plant. This Co loss would result in an additional operating cost of US\$1.2 million per annum for a direct Co EW flow sheet; however, the total Co losses would remain below the Co loss for the MHP flow sheet. Furthermore, this sludge could be recycled to the Fe removal circuit for the oxidation of Fe²⁺ to Fe³⁺, and the subsequent precipitation of Fe(OH)₃. This would be a process option only if Mn is oxidatively precipitated with Fe. High current densities, e.g. 250 A/m², resulted in a mixture of anode sludge and Co dendrites.

Table V. Anode sludge composition, % (m/m)

MnO	Co	Fe	Pb	Si	Mg	Cu	Ni	Ca	Cr	Al
54.3	16.2	0.8	0.7	0.2	0.2	0.2	0.1	0.1	0.1	0.1



Figure 8. Anode sludge layer

Cobalt electrowinning pilot-scale tests

Pilot-scale tests were conducted on the base case solution (Table II) to study primarily the morphology and the stress levels of the Co deposit (Table VI). The results are shown in Table VII.

Table VI. Test conditions for pilot-scale test work

Test number	Current density A/m ²	Applied current A	Feed flow rate L/h	Duration h
1	125	77	14	126
2*	125	77	14	126
3*	125	77	14	102
4*	250	153	28	100

*Tests were conducted without saccharin and thiourea additions

Table VII. Pilot test results

Test	Cell voltage V	Co deposition rate g/h/m ²	Current efficiency %	Power consumption kWh/kg Co	Co metal purity % Co (m/m)
125 A/m ² (additives)	5	36	26	18	97.7
125 A/m ² (no additives)	5	49	36	13	98.0
125 A/m ² (no additives)	5	55	40	12	98.2
250 A/m ² (no additives)	7	88	32	19	98.3

Cell voltage measured on the pilot plant was 5 V at 125 A/m², which was higher than the 3.4 V measured in the laboratory tests. The difference was due to a large inter-electrode spacing of 80 mm on the pilot plant compared to the 45 mm spacing in the laboratory set-up, which resulted in a high electrolyte resistance. The base case on the pilot test resulted in 26% current efficiency, which was 5% less than the laboratory test efficiency. As a result, power consumption on the pilot test was 8 kWh/kg Co higher than that achieved during the laboratory tests.

The base conditions were also run without addition of saccharin and thiourea. The absence of additives resulted in 10% increase in current efficiency and 5 to 6 kWh/kg Co reduction in power consumption. Current density was doubled to 250 A/m² and resulted in a significant increase in Co deposition rate. However, current efficiency decreased slightly and power consumption increased by 7 kWh/kg Co. The assays on the Co metal obtained from the pilot test work showed that the Co content was greater than 97% for all the tests.

Flow sheet simulations

Preliminary ‘direct’ Co EW design criteria

The laboratory and pilot-scale tests provided preliminary ‘direct’ Co EW performance criteria to be used in the simulations, namely:

- Current density: 125 A/m² (this should probably be increased to 150 – 175 A/m²)
- Power consumption: 10 kWh/kg Co
- Current efficiency: 30%
- 1.6 g/L Mg
- Co purity: >97%
- Anode-to-cathode spacing: 45 mm.

Flow sheet configurations

SysCAD software was used to simulate a Cu-Co flow sheet processing 1 576 800 t/a of typical DRC ore containing 3% Cu and 0.3% Co. The SysCAD base case flow sheet for MHP was derived from the block flow diagram in Figure 1, and the Co circuit is shown in Figure 7. The ‘direct’ Co EW flow sheet was the same as the base case flow sheet, with the Co precipitation step replaced by Co EW as shown in Figure 10.

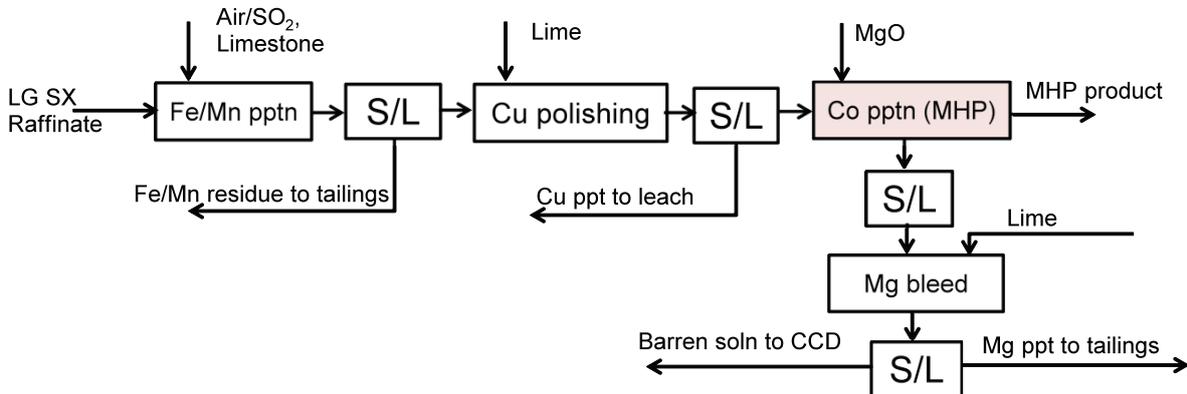


Figure 7. Base case flow sheet (MHP)

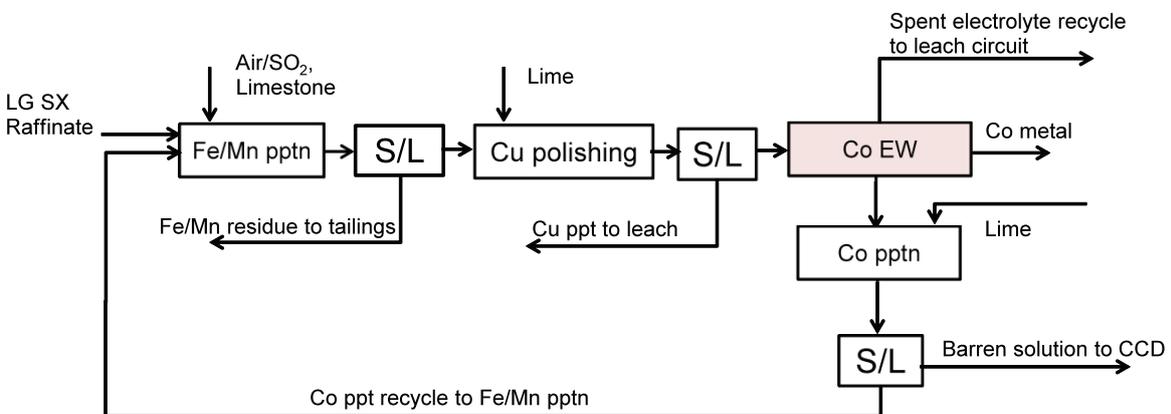


Figure 8. ‘Direct’ Co EW flow sheet

The main alteration to the typical Cu-Co flow sheet introduced by replacing MHP with direct Co EW was that a fraction of the Co EW spent electrolyte containing 2 g/L Co and 2.3 g/L H₂SO₄ was recycled to the leach circuit instead of the barren solution from the tailings dam. The remainder of the Co EW spent electrolyte was neutralized and the Co precipitated using lime, and after solid/liquid separation, the solids were recycled to the feed of the Fe/Mn circuit in order to build up the Co concentration to Co EW, and to consume some of the free acid entering in the feed to this circuit.

Two 'direct' Co EW flow sheets were evaluated, namely: one where Co EW spent electrolyte was recycled directly to the mill to maintain the solids density of 25% (m/m) (Co EW 1) and the other with spent electrolyte recycled to a second countercurrent decantation (CCD) stage that was added to the base case primary leach thickener (Co EW 2). A portion of the primary leach thickener overflow was used to control the solids density in the mill and the remainder was fed to high-grade Cu SX. The Co EW 2 flow sheet was configured in an attempt to increase the Co concentration in the Co EW feed due to the recycle of a portion of the primary leach thickener overflow (PLS) to the mill.

Three scenarios were evaluated for Co EW 1 and Co EW 2 flow sheets, namely Co EW with:

- Fe and Mn oxidative precipitation using air/SO₂ at pH 3.5 (F1)
- Fe precipitation only using air/SO₂ at pH 2.5 (F2)
- Fe precipitation only using air/SO₂, with the recycle of Mg via co-precipitation with Co (with 20% (m/m) lime slurry) on a portion of the Co EW spent electrolyte (F3). This was aimed at increasing the Mg concentration in the feed to the Co EW circuit to reduce the cell voltage by enhancing the electrolyte conductivity. A maximum of 4 g/L Mg in the feed to Co EW was achieved.

Reagent consumptions and Co losses

The reagent additions and Co losses obtained from the flow sheet simulations were used to compare indicative operating costs for MHP and direct Co EW. The Co recoveries, Co losses, and product purities are listed in Table VIII. The overall Co recovery for direct Co EW was slightly higher when compared to the base case MHP flow sheet. The Co losses in oxidative precipitation of Fe/Mn and Fe only using air/SO₂ were assumed to be 3% and 1% respectively, based on the relatively low pH values required for effective precipitation. As a result the precipitation of Fe only (F2) resulted in lower Co losses compared to Fe and Mn precipitation (F1).

Table VIII. Overall Co recovery and losses for Co precipitation and direct Co EW

Parameter	Base Case (MHP)	Co EW 1			Co EW 2		
		F1	F2	F3	F1	F2	F3
Co recovery, %	86	87	89	88	88	95	93
Co loss to tailings solids, %	14	13	11	12	12	5	7
Cobalt product purity, %	42	94	94	94	94	95	94

The Co content in the dried MHP product was 42% (m/m), assuming only 5% Mg (m/m) content. Operating plants often produce lower Co grades, primarily due to higher Mg contamination levels. The purity for the Co EW metal product was 94% according to the simulation.

Reagent additions resulting from the different flow sheet scenarios are listed in Table IX. Co EW 1 and Co EW 2 resulted in a 13% and 38% decrease in fresh acid addition in the leach respectively.

Table IX. Reagent consumptions for Co precipitation and EW

Parameter	Base case (MHP)	Co EW 1			Co EW 2		
		F1	F2	F3	F1	F2	F3
Cobalt losses, kg/t ore	0.4	0.4	0.3	0.4	0.4	0.2	0.2
Fresh acid, kg/t ore	55	49	49	49	37	37	37
SO ₂ , kg/t ore	50	51	53	53	51	53	53
Limestone, kg/t ore	65	69	73	54	69	73	54
MgO, kg/t ore	2.2	-	-	-	-	-	-
Power, kWh/kg Co	-	10	10	8	9	9	9
Total lime, kg/t ore	33	25	26	42	23	24	38

Mg recycle to Fe/Mn precipitation resulted in an increase in the Mg concentration, from 2 to 4 g/L in Co EW 1 and from 3 to 3.4 g/L in Co EW 2. The limestone addition in the Fe/Mn precipitation was lowered somewhat due to the neutralizing effect of recycled $Mg(OH)_2$; however, the increase in lime consumed by precipitating Mg and Co from the Co EW bleed stream was more significant. Hence, this option (F3) would markedly increase reagent costs.

Estimated revenue and total costs

The reagent additions and Co losses obtained from the various scenarios, together with the transport costs, were used to estimate preliminary indicative operating costs using the commodity prices listed in Table X. Co product revenues were calculated based on the LME Co price, assuming 60% and 90% of the LME Co values for the MHP and Co metal respectively.

Table X. Commodity prices

Acid, US\$ per ton	480
MgO, US\$ per ton	1425
Limestone, US per ton	250
Lime, US\$ per ton	618
Flocculent, US\$ per tont	7405
Electricity, US\$ per kWh	0.05
Fresh water, US\$ per litre	0.005
Transport costs, US\$ per tont	500
Cobalt hydroxide price, US\$ per ton	19842
Cobalt metal price, US\$ per ton	29762
LME Copper metal price, US\$ per ton	7364
LME Cobalt metal, US\$ per ton	33069

Co EW 2 flow sheet with Fe precipitation, i.e. Co EW 2-F2 in Table XI, resulted in maximum Co revenue (US\$147 million) and minimum operating costs (US\$249 million), hence this option appeared to be the best option. The reduction in operating costs was due mainly to a decrease in reagent and product transportation costs, Co losses, fresh acid for the leach, lime, and limestone. These costs are indicative only and preliminary feasibility studies are required to finalise the process selection. However, the 65% increase in Co product revenue achieved by the direct Co EW flow sheet would be the primary driving force for considering the direct Co EW technology.

Table XI. Indicative operating costs and revenue comparisons

US\$ million per annum	Base case (MHP)	Co EW 1			Co EW 2		
		F1	F2	F3	F1	F2	F3
Total opex	303	275	281	288	251	249	253
Co Revenue	89	136	139	136	137	147	144

Conclusions

Laboratory tests showed that direct Co EW was feasible, although current efficiency was relatively low. The optimum current density at a 1.5 g/L delta Co was 175 A/m², and it resulted in 34% current efficiency and 10 kWh/kg Co. Although energy consumption would be at least twice that for conventional Co EW, the cost of energy would still be slightly lower than the cost of MgO required for MHP. Furthermore, reagent transport cost associated with MgO would result in lower operating costs for Co production via direct EW.

Process simulations results for the Cu-Co ore showed that direct Co EW was a potential alternative to the MHP flow sheet due to the indicative lower operating costs and the high-quality product, which translate to a major potential increase in the Co revenue. The major contributor to the cost savings was reduced transport costs of reagents and Co product for the Co EW when compared to the MHP flow sheets. The optimum Co EW scenario resulted in a 22% decrease in operating costs. The higher Co quality would most probably result in a 65% increase in the Co revenue

compared to the base case MHP flow sheet. The Co product revenue would therefore be the main driver of the direct Co EW technology.

A demonstration pilot plant and prefeasibility studies are required to validate the experimental results and prove the process economics of the technology.

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