Advances in Cobalt Recovery and Purification

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In cooperation with industry, in-depth research was conducted at Mintek to assess, improve and innovate technologies with the key objective to optimise recoveries while minimising operating costs and environmental impact. A combination of bench-scale and pilot plant testwork, combined with mineralogical analyses and flowsheet simulations made this possible. This has resulted in the development of multiple patented technologies for the recovery and purification of cobalt, such as the MgO recycling technology, direct Co electrowinning and the air/H_2SO_3 technology. A further inclusion is the application of the Nicksyn™ synergist in cobalt purification circuits as alternative to the conventional solvent extraction configurations. Furthermore, processes were developed to generate ultrapure cobalt metal and salt for the use in batteries. Successful pilot campaigns have been conducted for these cobalt recovery processes and their performance and features are presented in this paper.

INTRODUCTION

The industry is currently experiencing a resurgence of cobalt as it is used in energy storage devices, mostly for electric cars. This resurgence has sent the cobalt price soaring to currently USD ~80 000 per tonne of London Metal Exchange (LME) grade cobalt. During the previous surge in metal prices in the mid-to late 2000s a vast amount of bench-scale testwork and a multitude of continuous integrated pilot-plant campaigns from ore to Cu and Co metal were conducted at Mintek. These included the unit operations of leaching, solid–liquid separation, precipitation, solvent extraction (SX), ion exchange (IX) and electrowinning (EW).

This experience enabled in-depth research to assess, improve and innovate technologies with the key objective to optimise recoveries while minimising operating costs and environmental impact. Cooperation with industry, such as clients, design houses, equipment and reagent manufacturers and suppliers has resulted ultimately in the development of multiple technologies for the recovery and purification of cobalt. The main innovations presented in this paper are the:

- $Mg(OH)_2$ recycling technology;
- Direct Co EW technology;
- Air/H_2SO_3 technology;
- Inclusion of the synergistic Nicksyn™ reagent in Co purification circuits;
- Generation of ultra-pure cobalt salt and cobalt metal for the use in batteries.

These technologies have now matured to a stage at which demonstration on a specific site or inclusion into current processing plants warrants serious contemplation.

$Mg(OH)_2$ RECYCLING TECHNOLOGY

Background

MgO is often used as a neutralizing agent for the recovery of cobalt mixed hydroxide precipitates, as it produces a higher quality precipitate compared with the precipitate obtained when lime is used as neutralizing agent. The high cost of the MgO reagent increases the operating costs of a cobalt recovery circuit. Moreover, build-up of Mg in process streams, associated with the utilisation of MgO as precipitation reagent, as well as the release of Mg during leaching of ores, can increase the viscosity of the process stream. This can, in turn, adversely affect downstream processes, such as the solid–liquid separation performance with knock-on effects on the Cu SX–EW circuits due to solids carryover. Hence, the barren stream from the cobalt purification circuit should be neutralised to precipitate and bleed Mg before recycling the barren stream as process water. Since this generates an effluent stream which contains both magnesium hydroxide and calcium sulphate (gypsum), it led to the development of a patented (Kotze, 2012) $Mg(OH)_2$ reagent recovery and recycling technology. This technology reduces the use of fresh MgO in order to increase the profitability of the process while utilising the precipitate generated in such Mg precipitation step. In addition to the reduced operating cost, reagent recycling could potentially minimize the footprint of lined tailings ponds resulting in capital cost (CAPEX) savings. A simplified Co recovery (Flowsheet 1) is compared with a cobalt recovery flowsheet incorporating $Mg(OH)_2$ recycle technology (Flowsheet 2) in Figure 1. Both flowsheets are similar, the only difference being the recycle of $Mg(OH)_2$ in the base metal precipitation step integrated at the back-end of the circuit. Thus, the implementation of the process does not impact on the ongoing main operation at all and therefore is a low risk endeavour with potentially high cost savings (Mokoena and Pawlik, 2016).

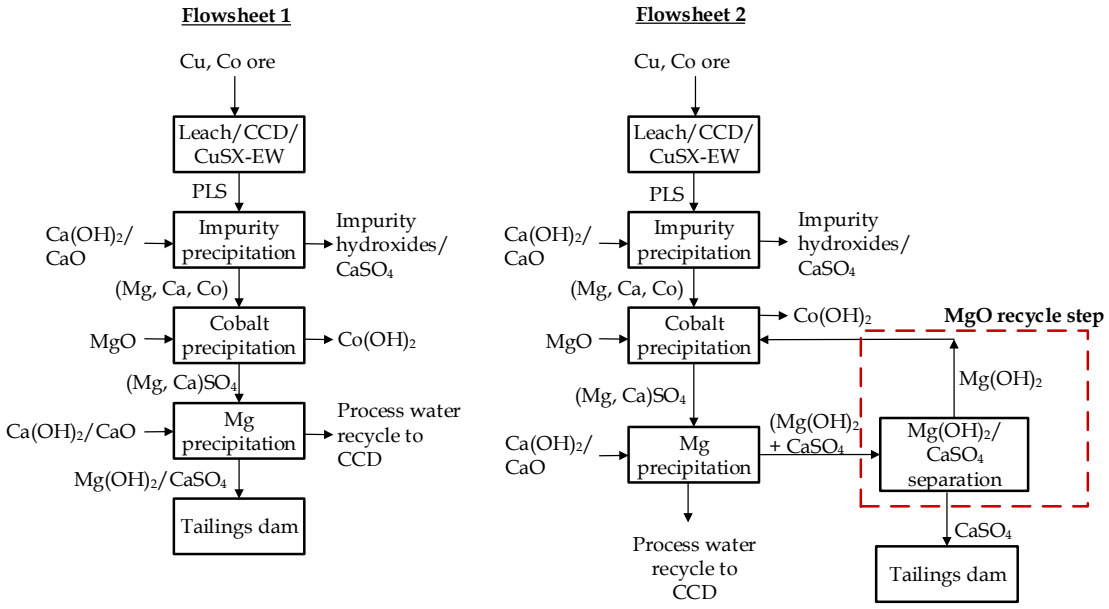


Figure 1: Simplified illustration of typical cobalt recovery flowsheets with and without $Mg(OH)_2$ recycle step (adapted from Mokoena and Pawlik,2016)

Technical Facts

The process is based on the successful separation of $Mg(OH)_2$ particles from the gypsum ($CaSO_4 \cdot 2H_2O$) particles. Various techniques, including cycloning, centrifuging, gravity concentration and elutriation were evaluated. The comparison of the performance of the different techniques indicated that elutriation was the most favourable process. The most suitable device found for elutriation was the REFLUX™ Classifier (RC) manufactured by FLSmidth. A picture of the actual demonstration-type RC simulation rig used for the testwork is shown in

Figure 2. A more detailed description of the functionality of the RC within this system can be found in Mokoena and Pawlik (2016).

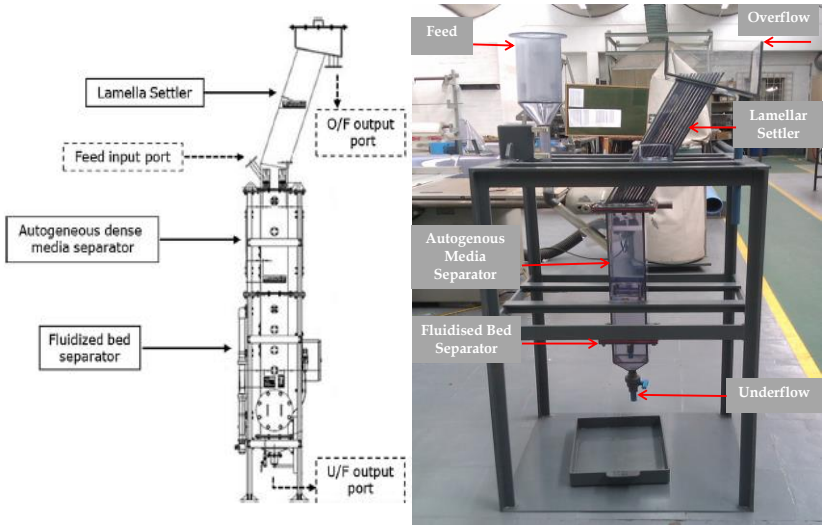


Figure 2: Schematic illustration of a REFLUX™ Classifier and the Demo-RC used for test work.

Once the operating parameters of the RC had been optimised in small-scale tests, a fully integrated semi-continuous demonstration plant campaign for the duration of 3 days was commissioned. It included the $Mg(OH)_2$ precipitation step with solid–liquid separation and seed recycle. The REFLUX™ Classifier and a cobalt precipitation circuit using synthetic cobalt solution (~5.5 g/L Co) were integrated. The synthetic cobalt solution was treated with the recovered $Mg(OH)_2$ to produce a cobalt hydroxide product. The reactivity of the recovered $Mg(OH)_2$ from the third day of operation was compared with that of fresh MgO samples from two different suppliers. The chemical compositions of the recycled MgO and fresh reagents are presented in Table 1, while a summary of reactivity results is presented in Table II. Micrographs of separated magnesium hydroxide and gypsum phases are presented in Figure 3. A more detailed discussion of the results is contained in Mokoena and Pawlik (2016).

Table 1: Chemical composition of the recovered $Mg(OH)_2$ (Mokoena and Pawlik, 2016).

Sample ID	Mg	Calculated $Mg(OH)_2$	S	Calculated $CaSO_4.2H_2O$	Calculated $Ca(OH)_2$
	(%m/m)				
Recycled $Mg(OH)_2$	26	63	3.4	18	5.9
Supplier A	57.5	95	–	–	–
Supplier B	47.2	78	–	–	–

Table II: Co precipitation comparing recovered $Mg(OH)_2$ and fresh MgO (Mokoena and Pawlik, 2016).

Reagent	$Mg(OH)_2$ addition (stoichiometry)	Co precipitation extent	Mg utilisation	Mg in precipitate	Ca in precipitate	Co in precipitate
	(%m/m)					
Recycled $Mg(OH)_2$	52	66	91	1.3	1.3	46
Supplier A	80	77	88	2.2	1.3	48
Supplier B	80	64	85	2.6	1.1	43

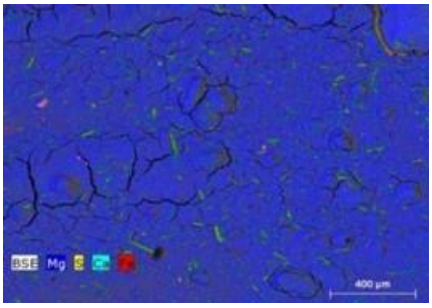
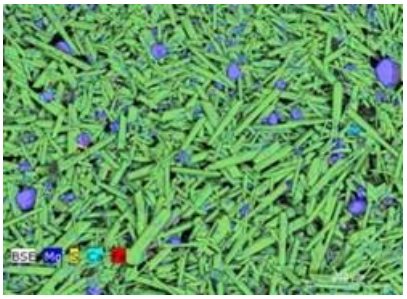
(A)  (B) 

Figure 3: Scanning electron microscopy images of (A) overflow ($Mg(OH)_2$) and (B) underflow ($CaSO_4 \cdot 2H_2O$) products generated.

The results of the testwork proved the following (Mokoena and Pawlik, 2016):

- A clean separation of Mg hydroxide from gypsum is possible at Mg recoveries up to ~70% with less than 20% gypsum entrainment.
- A $Mg(OH)_2$ grade of 63% was attained in the Mg product with gypsum contributing 18% and unreacted lime 6%.
- The Mg hydroxide product received from the RC overflow can be fed directly to the Co precipitation step without further dewatering or other treatment.
- No ageing of the $Mg(OH)_2$ was evident and the utilisation of Mg in the Co precipitation test was 91%. This was higher than the utilisations of Mg from the fresh MgO supplied.
- A cobalt cake with a Co grade of 46% m/m was produced using recycled $Mg(OH)_2$ and the contamination of the product with Mg and Ca was minimal (1.3% m/m Mg and 1.3% m/m Ca, respectively).

Techno-Economics

Table III presents the estimated operating cost (OPEX) savings as a function of $Mg(OH)_2$ recovery for a cobalt production plant with a mixed hydroxide product (MHP) output of 10 500 t/a, assuming an MgO price of USD 1,400/t reagent. The capital investment was based on a REFLUX™ classifier unit with a capacity of 30 t/h to service a 7000 t/a cobalt production plant. The cost was in the range of USD 159,000 to USD 198,800. A detailed discussion of the results is contained in Mokoena and Pawlik (2016). The main outcomes of the study are listed below.

- OPEX savings based on fresh MgO reagent costs at 71% $Mg(OH)_2$ recovery at a $Mg(OH)_2$ grade of 87% was calculated to be USD 2,862,800 per year.
- The OPEX savings associated with $Mg(OH)_2$ recycle could potentially recoup the cost of the RC within one month of operation.
- Approximately 75% Mg recovery appears sufficient to maximise OPEX savings. Beyond this point, there is no significant improvement.

Table III: Potential operatingcost savings as a function of $Mg(OH)_2$ recovery (Basis: 10 500 t/a MHP production) (Mokoena and Pawlik, 2016).

$Mg(OH)_2$ recovery in solid–solid separation (%)	Mass of MgO saved (t/a)	OPEX savings (USD/a)	OPEX savings (USD/month)
0	0	–	–
25	912	942,749	78,562
50	1824	1,885,498	157,125
75	2736	3,582,447	235,687
100	3648	3,770,997	314,250

DIRECT COBALT ELECTROWINNING

Background

MgO is typically used for the recovery of cobalt as an MHP. MgO is an expensive reagent and hence the operating costs of the Co precipitation circuit are high. Furthermore, the MHP ideally only contains ~40-45% m/m Co if dried; if wet, the Co concentration could drop to ~25–30%. This means that transport costs are also incurred for the barren material associated with the Co in the MHP. The patented (Kotze and Tripathy, 2012) direct cobalt EW (CoEW) technology was developed with the aim of eliminating these disadvantages by circumventing the use of MgO and to decrease the transport cost per unit of cobalt. There was a further expectation that the product, due to its higher grade, could potentially yield a higher price. Figure 4 compares the conventional Co MHP flowsheet (Figure 4a) with a Co flowsheet with integrated direct CoEW (Figure 4(b)). The CoEW step replaced the two Co precipitation stages, thus eliminating both MgO for the primary precipitation and lime addition for the secondary precipitation.

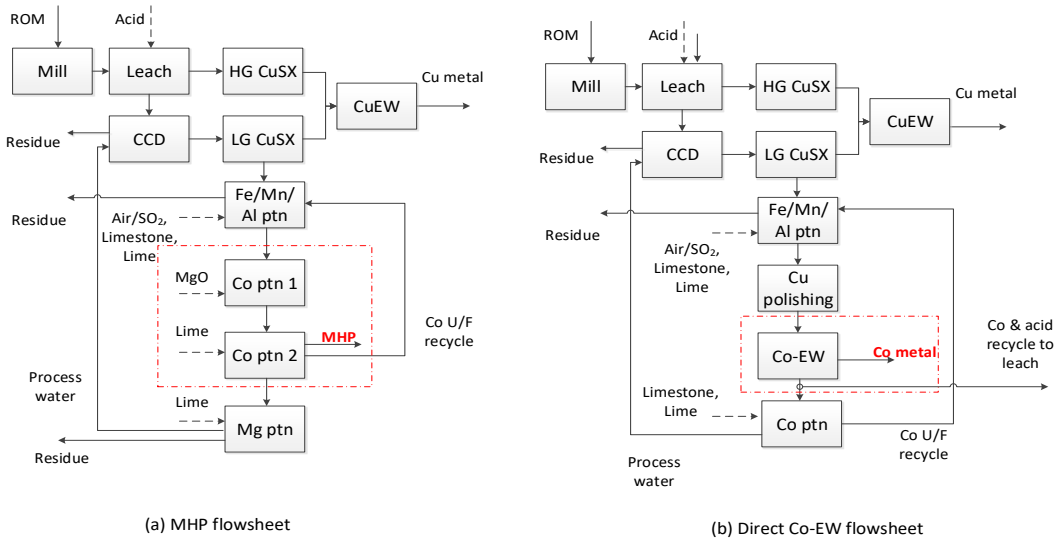


Figure 4: (a) MHP flowsheet and (b) direct CoEW flowsheet

Technical Facts

After optimising the test conditions in the laboratory, a pilot plant using industrially sized electrodes was conducted. The total cathode area was 1.74 m² and the process targeted an average ΔCo of 2 g/L. Three tests were conducted at varying conditions as shown in Table IV, the feed solution composition is listed in

Table V. Images of the cathodes are shown in Figure 5 (Mulaudzi, 2017). In terms of deposit morphology, the deposit obtained at 175 A/m² was notably rougher and more nodular compared to the deposit at obtained 150 A/m². The deposit at 175A/m² was in addition extremely porous (Mulaudzi, 2017).

Table IV: Industrial-scale direct CoEW testwork performance.

Test number	Current density (A/m²)	Test duration (d)	Average cell voltage (V)	Current efficiency (%)	Power consumption (kWh/kg Co)	Co deposition rate (g/h/m²)
1	150	12.0	3.8	21	17	27
2	175	12.7	4.1	15	25	29
3	150	15.0	3.7	23	15	38

Table V: Feed solution composition.

Element	Co	Mg	K	Ca	Mn	Na	Ni	Cu	Zn
Unit	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L
Concentration	4.22	2.14	1.20	0.58	0.20	0.08	0.01	0.01	0.01

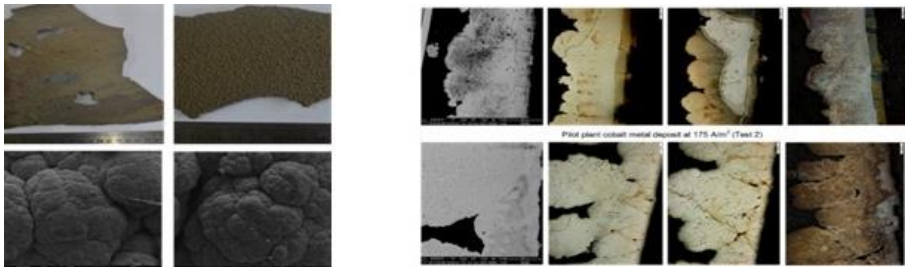


Figure 5: Surface morphology and cross sectional images of pilot-plant cobalt deposits for Tests 1 and 2.

Table VI and VII (Mulaudzi, 2017) show the assays of the cathodes generated in Tests 1 and 2 in comparison with the specifications for Low Grade (LG) LME cobalt and

Table *VIII* shows the cathode purities. Specifications were met except for Ca, Cu, Zn (only Test 1) and Pb. The high Cu and Zn grades can be explained by their presence in the feed solution. The high Ca grade may be a result of supersaturation with $CaSO_4$, leading to precipitation of gypsum on the cathode surface followed by occlusion with Co. The contamination with Pb was likely caused by the Pb–Ag anodes.

Table VI: Direct cobalt electrowinning cathode composition for industrial-scale tests: major impurities.

Element (mg/kg)	Ca	Ni	Cu	Pb	Zn	Se	As	Fe	H	N	Sb	Ag
Test 1 (150 A/m²)	3297	1820	4397	3180	870	593	157	173	1825	265	1.3	6.0
Test 2 (175 A/m²)	3300	2020	5090	1705	330	648.5	155	52	885	125	1.4	5.0
LG LME Co Spec	< 250	< 5500	< 200	< 100	< 500	–	–	< 2000	–	–	–	–

Table VII: Direct cobalt electrowinning cathode composition for industrial-scale tests: trace impurities

Element (mg/kg)	Al*	Mg	Si	Ti	V*	Cr	Mn	Cd*	Sn	Bi	S*	O
Test 1 (150 A/m²)	0.5	1.0	1.0	0	0.1	0.9	0.6	0.2	0.7	0.1	0.0001	0.0005
Test 2 (175 A/m²)	0.5	1.0	1.0	9	0.1	0.6	0.7	0.2	0.7	0.1	0.0001	0.0004
LG LME Co Spec	–	< 250	–	–	–	–	< 1000	< 100	–	–	< 500	–

*Concentration below detection limit

Table VIII: Direct cobalt electrowinning cathode purity.

	Total impurities (mg/kg)	Co (mg/kg)	Total impurities (% m/m)	Cobalt purity by difference, (% m/m)	Co purity (based on Co assays-normalised) (% m/m)
Test 1 (150 A/m²)	16 588	988 000	1.66	98.34	98.35
Test 2 (175 A/m²)	14 329	961 500	1.43	98.57	98.53
LG LME Co Spec	7 408	–	0.74	>99.26	–

Techno-Economics

A techno-economic evaluation using a discounted cash flow (DCF) model was done by DRA Global on a bare-bones basis, in real terms meaning it does not consider the effects of taxes, interest, financing models or any escalation; a 10% discount rate was used. Note that the costs shown are not to be regarded as definitive, but rather differential costs.

Capital cost comparison basis

An extensive spreadsheet-based analysis model was developed for this evaluation. The direct CoEW process input used for the calculations was a current efficiency of 35% at 150 A/m². All equipment was of standard supply. The main CAPEX considerations include:

- Differences in major mechanical equipment;
- Typical design criteria for each flowsheet in support of mass balancing and equipment sizing;
- Mechanical equipment costs determined from recently executed studies as well as DRA's internal database;
- Internal DRA factors applied for civils, structural (supply and erection), platework (supply and erection), mechanical erection, piping (supply and installation), electrical, control and instrumentation (supply and installation), transport, project services, and Preliminary and General costs (P&Gs).

Operating cost comparison basis

OPEX estimates and process design citeria (PDC) were based on the outcomes of mass balances conducted using the *SysCAD*® simulation package. Triangular distributions were applied to account for uncertainty associated with the mass balance results. Reagent costs from the DRA database were used to calculate the OPEX, which included:

- Reagent costs estimated from the DRA reagent supply database;
- Reagent consumption rates, determined from high-level mass balances, and include: sulphuric acid for leach; lime, limestone and MgO for pH control and to effect precipitation within the eight relevant unit operations; SO_2, in conjunction with air, for the oxidation of Fe and Mn in the Fe/Al/Mn precipitation step;
- Power, labour and operating maintenance calculated did not have a significant effect on the differential OPEX.

The results from the flowsheet simulations showed that the OPEX for the Direct CoEW flowsheet was 27% lower than that of the MHP flowsheet. This was primarily due to the elimination of MgO from the flowsheet, and consequently reduced $Ca(OH)_2$ requirement for Mg precipitation. The dry mass of the MHP (40% (m/m) Co) was three times the mass of Co metal mass (97% (m/m) Co), which resulted in a 63% reduction in transport costs (Mulaudzi and Archer, 2015). The techno-economic evaluation results indicated that the direct CoEW flowsheet has a notable potential benefit as compared with the MHP flowsheet. The expected differential mean net present value (NPV) for direct CoEW flowsheet could potentially increase by USD 100 million compared with the MHP flowsheet. The highest CAPEX calculated for the direct CoEW flowsheet would result in an additional USD 42 million expenditure. It was also found that the power required for CoEW was offset by the power required for the MHP drying plant (Mulaudzi and Archer, 2015). Considering the nominal/mean values obtained from the various mass balance simulations conducted, the OPEX savings would result in a potential higher mean NPV of USD 74 million. The sensitivity analysis showed that the main model driver was the uncertainty associated with the Co recovery for both flowsheets (Figure 6). The Co price was also a factor, although it did not have as significant an effect on the NPV (Mulaudzi and Archer, 2015). Currently the Co price cannot be benchmarked accurately as this is a new product and currently no market exists. A potential disadvantage of such Co metal over MHP would be the difficulty of re-dissolution for further refining.

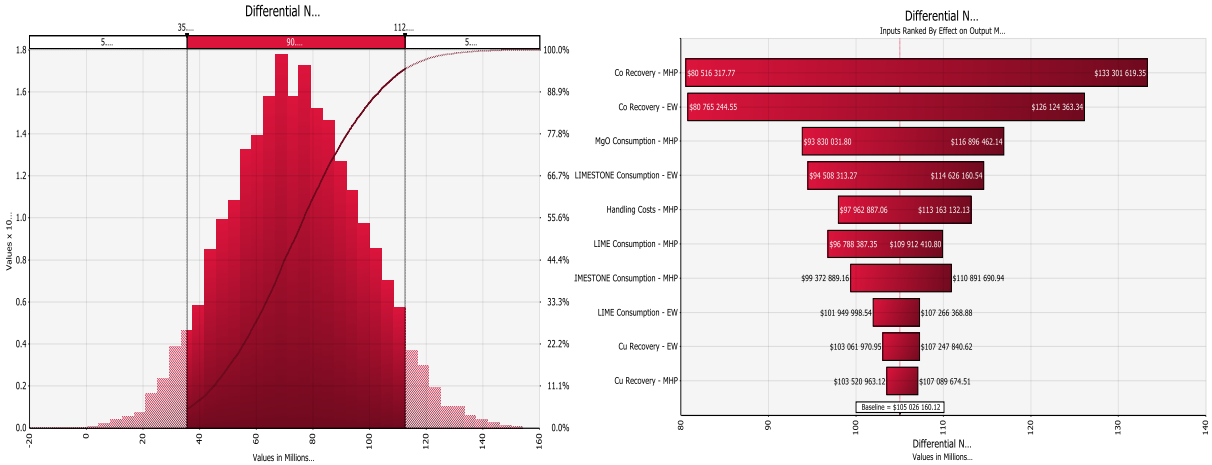


Figure 6: Differential net present value and sensitivity analysis for Direct CoEW (Mulaudzi and Archer, 2015).

AIR/H_2SO_3 TECHNOLOGY

Background

The processing of cobalt ores often results in the deportment of impurities such as iron and manganese to the solution. These contaminants need to be removed from leach solutions prior to downstream processing. Numerous studies have been conducted investigating the removal of iron and manganese from cobalt-rich solutions using a gas mixture of air and sulphur dioxide. Owing to the operational challenges associated with the use of SO_2/air, such as liquefaction in pipes and hence inconsistent flow, the Mintek team then refocused on the potential use of sulphurous acid (H_2SO_3)/air for removal of Fe and Mn, which would allow a more consistent and controllable performance.

Technical Facts

The patented (Schoeman and Kotze, 2011) air/H_2SO_3 technology requires an SO_2 scrubber; SO_2-containing gas (typically from burner off-gas on an industrial acid plant) which is fed to the scrubber and the SO_2 is dissolved to form sulphurous acid. The sulphurous acid is then fed at the required rate to the Fe/Mn/Al (FMA) removal step. In conjunction with this, air or oxygen is sparged into the FMA removal tanks. O_2 in conjunction with SO_2 forms a powerful oxidant to convert Fe(II) to Fe(III) and Mn(II) to Mn(III/IV), both of which are insoluble at the specific operating conditions and hence removed from the Co-bearing liquor. To maximise oxygen mass transfer into solution, specially designed impellers are required, which EKATO designed. The SO_2 scrubber system to dissolve SO_2 in water used for piloting purposes was provided by MECS Africa. The SO_2 gas entered the top of the scrubber where it mixed with water, which was sprayed upward counter to the gas flow. A turbulent zone was created where the gas collided with the liquid and formed a froth zone where the gas/liquid interface was continuously and rapidly renewed. The EKATO agitator comprises dual impellers (see Figure 7*), namely the EKATO Combijet and the EKATO Viscoprop. Air was introduced underneath the EKATO Combijet, which has the main function of dispersing added gas via radial flow ("shear") to facilitate oxygen mass transfer. The process is typically conducted at 45°C and limestone slurry is used to control the pH. In the first tank, the pH is adjusted to 2.5 so as to neutralise free acid present in the solution. From the second to the sixth tanks, air and sulphurous acid are introduced into the system. The operating is typically between pH 3.5 and 4.2. The typical process parameters and precipitation kinetics of Fe, Mn and Cu are illustrated in*

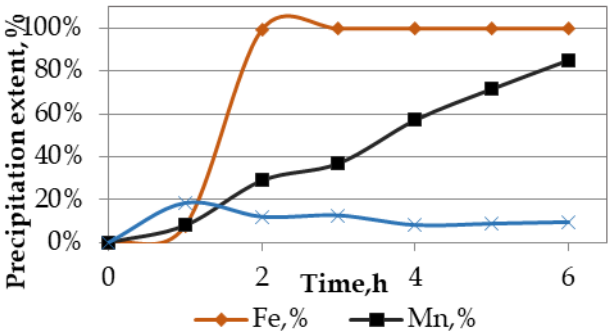


Table IX and

Figure 8.

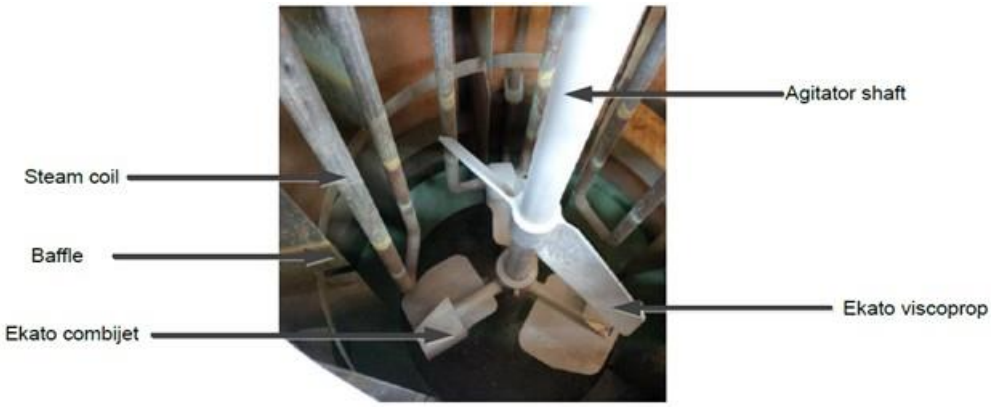


Figure 7: An illustration of the interior of the 2 m³ test rig with EKATO Combijet impeller.

Table IX: Process performance of Fe/Mn removal with the air/H_2SO_3 system.

$CaCO_3$ consumption (kg/kg Co in feed)		2.9		
H_2SO_3 consumption (kg SO_2/kg Co in feed)		0.39		
Element	Fe	Co	Mn	Cu
Concentration of metal in synthetic solution (mg/L)	1085	7800	689	162
Grade of metal in precipitate (%)	2.9	0.1	1.5	0.05
Concentration of metal in barren solution (mg/L)	2	7400	89	143
Precipitation efficiency based on solution (%)	99	0.5	85	10

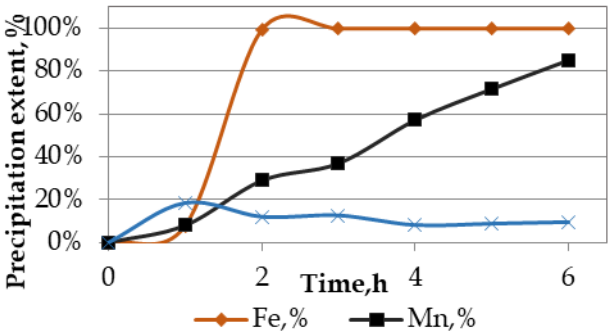


Figure 8: Precipitation kinetics of Fe, Mn and Cu under typical operating conditions.

VERSATIC 10 ACID/NICKSYN™ SYNERGISTIC SYSTEM VERSUS D_2EHPA AND CYANEX 272 FOR THE RECOVERY OF COBALT

Background

The production of premium-grade cobalt cathode requires stringent control of impurity concentrations in the cobalt advance electrolyte to obtain >99.3% electrowon cobalt. As an alternative to the typical di(2-ethylhexyl)phosphoric acid (D_2EHPA) and di(2,4,4-trimethylpentyl)phosphinic acid (Cyanex 272) SX unit operations, the use of a synergistic system using Nicksyn™ synergist combined with Versatic 10 acid was evaluated. A desktop trade-off study was conducted by DRA Global and Mintek (Archer *et al*., 2014), in which estimated cash flow differentials were used to evaluate the two flow sheets. A stochastic economic model was used to estimate the revenue CAPEX and OPEX using discounted cash flow techniques. The options compared are listed below:

Option 1: Bleed→ Fe/Al ppt→ D2EHPA SX→ Cyanex 272 →SX Cu-Zn IX→ Co EW
Option 2: Bleed→ Fe/Al ppt→ NickSYN™+V10 SX→ Cu-Zn IX → Ni IX→ Co EW

Technical Facts

Cyanex 272 circuit: Selectivity: Mn > Co > Mg > Ca > Ni

- Mn is extracted quantitatively and reports to the EW circuit. Some Mn precipitates at the anodes as MnO_2. The majority Mn has to be bled from the EW circuit.
- Co is recovered via selective precipitation. Treatment of this bleed stream for Co recovery is costly, as Co has to be recycled to various Co purification circuits, incurring additional Co losses.
- Cu and Zn present in the solution are co-extracted by Cyanex 272.
- Optimum Co recovery is targeted, some Mg will be co-extracted (while Ca will be rejected). Mg has to be scrubbed from the organic, or bled from the EW circuit.

D_2EHPA circuit (Mn and Zn removal): Selectivity: Zn > Ca > Mn > Co > Ni

- If relatively efficient Mn extraction is targeted, Ca will co-extract to a larger extent, and some Co will be co-extracted.
- Co loss should be limited by scrubbing of the loaded organic phase.

V10/Nicksyn™ circuit: Selectivity: Cu > Ni > Zn > Co > Mn > Ca ≈ Mg

- Ni and/or Co can be extracted from Mn, Ca and Mg when Cu and Zn are not present.

Trade-Off Study

For the Nicksyn™/Versatic 10 synergistic system and the D_2EPHA/Cyanex 272 circuit, conceptual PDC were developed and a cost estimation was completed to determine the likely differential CAPEX and OPEX for these two circuits. *Figure 9* provides a scatter plot of estimated CAPEX and OPEX for both options, where error bars represent the 90% confidence band (Archer *et al*., 2014). The positive

differential, as well as lower differential CAPEX and OPEX, is in favour of the V10/Nicksyn™ option. Despite the marginal reduction in metal output, the synergistic circuit is estimated to provide a pre-tax NPV improvement of USD 20m to USD 70m over a 10-year life of mine (Archer *et al*., 2014).

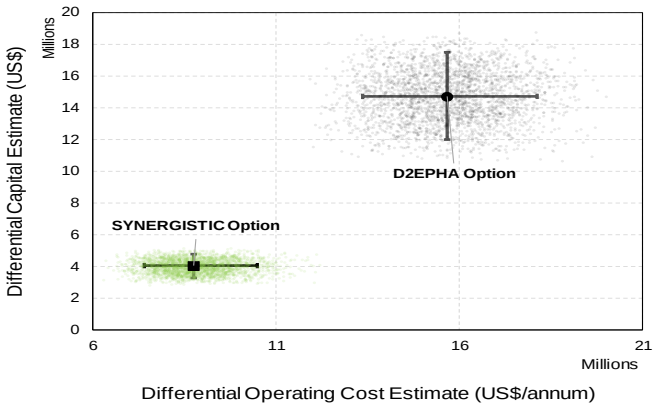


Figure 9: Scatter plot of estimated capital and operating costs for D_2EHPA and V10/Synergist options (from Archer et al., 2014).

FURTHER DEVELOPMENTS

Ultra-Pure Cobalt Salt and Metal

The demand for ultra-pure cobalt metal and cobalt salts, mainly by the battery industry, will require a reliable and cost effective process to be introduced by cobalt refineries. The specifications are very stringent, usually not exceeding 10 ppm or less per impurity in the salt or metal. This means that most impurities have to be removed to a tenor of <0.1–1 mg/L in the process solution. Such a process has been piloted successfully for cobalt. This process is based on the use of IX for the extraction of impurities as it is believed to be the most attractive for this type of process. There is, however, a shortage of commercially available resins for this type of process. This resulted in the use of solvent-impregnated resins (SIRs), which feature the beneficial properties of resins and take advantage of the wide variety of extractants commercially available for SX applications. A further advantage is that these SIRs could be generated on site using a blank resin and contacting it with the organic extractant. The cobalt stream typically treated originates from the raffinate bleed stream and should be Fe- as well as Al-free. Hence, the barren liquor from the Fe/Mn/Al precipitation step would constitute a suitable feed; noting, however, that the cobalt tenors might be too low in cases. A re-leached MHP at Co tenors of ~50–60 g/L would constitute an ideal feed stream. Currently, further developments are taking place, seeking expansion into other applications, as well as seeking further SIR combinations and improvements to further simplify the process for producing battery-grade cobalt. Research into anodes for electroplating that would not contaminate the Co metal with Pb or Ag is required; alternatively, the use of divided cells is indicated. Melting of the cathodes, though energy-intensive, showed that any Pb, Zn or Cd contamination could be removed as at such temperatures these elements fume off from the metal.

CONCLUSIONS

Over more than a decade, a vast amount of bench-scale testwork and a multitude of continuous integrated pilot-plant campaigns have been conducted at Mintek, from ore to Cu and Co metal in cooperation with the industry. As a result of this expertise, multiple patented technologies and know-how have been developed. These are aimed at improving and innovating technologies to maximise recoveries while minimising operating costs and environmental impact. Over the years, the

technologies have matured and are now at a stage where commercial implementation can be considered.

The Magnesium Hydroxide Recycle Technology is a risk-free installation on site as the process is integrated at the tail of the operation. A clean separation of $Mg(OH)_2$ from gypsum is possible at Mg recoveries up to ~70% with a grade of 63% $Mg(OH)_2$. The recycled Mg hydroxide product can be fed directly to the Co precipitation and had a utilisation of Mg in the Co precipitation test of 91%. This was higher than the utilisations of Mg from the fresh MgO supplied. The cobalt cake generated using recycled $Mg(OH)_2$ had a Co grade of 46% m/m and the contamination of the product with Mg and Ca was minimal. Hence, this technology promises extensive reagent cost savings and the cost of the capital may be recouped within a month of successful operation.

Direct cobalt EW was piloted using industrially sized electrodes with an impure raffinate stream as feed. All specifications for LG LME Co cathode were met except for Ca, Cu, Zn and Pb. Nonetheless, a purity of 98.3–98.6% m/m Co was achieved. The results from the flowsheet simulations showed that the OPEX for the Direct CoEW flowsheet was 27% lower than that of the classical MHP flowsheet. The expected differential mean NPV for direct CoEW flowsheet could potentially increase by USD 100 million compared with the classical MHP flowsheet. The highest CAPEX calculated for the direct CoEW flowsheet would result in an additional USD 42 million expenditure. It was also found that the power required for CoEW was offset by the power required for the MHP drying plant.

The Air/H_2SO_3 technology uses sulphurous acid introduced into the process liquor for oxidative Fe and Mn removal due to the operational challenges associated with the conventional use of SO_2/air. These include as liquefaction in pipes and hence inconsistent flow and performance. The performance of the technology was proven on a 2 m^3 demonstration rig removing >99.9% Fe within 2 h and 85% of the Mn in 6 h.

For the Nicksyn™/Versatic 10 synergistic system and the D_2EPHA/Cyanex 272 circuit, conceptual process design criteria were developed and a cost estimation was completed to determine the likely differential CAPEX and OPEX for these two circuits. The positive differential, as well as lower differential CAPEX and OPEX, is in favour of the V10/Nicksyn™ option. Despite the marginal reduction in metal output, the synergistic circuit is estimated to provide a pre-tax NPV improvement of USD 20m to USD 70m over a 10-year life of mine.

The demand for ultra-pure cobalt metal and cobalt salts, mainly by the battery industry, will require a reliable and cost-effective process. Such a process for has been successfully piloted for cobalt. This process is based on the use of IX for the extraction of impurities. There is, however, a shortage of commercially available resins, which resulted in the use of SIRs featuring the beneficial properties of resins and benefit from the wide portfolio of extractants commercially available for SX applications.

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