

# The recovery of nickel and cobalt from a sulphate bioleach solution using Dow M4195

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The application of ion exchange technology for the recovery of nickel and cobalt from a sulphate bioleach solution is discussed. The suitability of Dow M4195 (bispicolylamine functionality), Dow XUS43605 (hydroxypropylpicolylamine functionality), and Amberlite IRC748 (IDA functionality) to achieve the desired separation was evaluated.

Screening experiments indicated that Dow M4195 has the highest selectivity towards nickel and cobalt over other dissolved metals (iron, zinc, manganese, and aluminium), and that this resin has superior iron rejection compared to IDA-type resins. Batch adsorption kinetic experiments showed that the rate of nickel adsorption on Dow M4195 could be described by a second-order approach to equilibrium model. Langmuir and Freundlich isotherm models were fitted to the batch nickel adsorption equilibrium data and maximum nickel capacities of 22.72 g/l and 30.86 g/l were observed at pH values of 2 and 4 respectively.

The effects of flow rate, temperature, pH, and initial metal concentrations on the dynamic recovery of nickel and cobalt were investigated in fixed-bed columns. It was determined that the temperature, flow rate, and the interaction of these two parameters had the most significant impacts on the loading of nickel and cobalt on Dow M4195 at initial nickel breakthrough. For a flow rate of 5 bed volumes (BV) per hour and an initial solution pH of 4, the nickel loading on the resin at 1% nickel breakthrough increased by 105% when the temperature was increased from 25°C to 60°C.

Finally, split elution of cobalt and nickel from Dow M4195 was investigated. Near complete elution of cobalt and 27% nickel elution were achieved when using 3.5 BV of 20 g/l H<sub>2</sub>SO<sub>4</sub> as the eluant at a flow rate of 10 BV/h and a temperature of 60°C. A nickel-rich eluate could then be obtained by subsequently treating the resin with 3.5 BV of 200 g/l H<sub>2</sub>SO<sub>4</sub> to recover the remainder of the adsorbed nickel.

## Introduction

### Background

Potential leaching process routes for the recovery of base and precious metals from a low-grade PGM-bearing ore were investigated by Mwase (2009) and Mwase et al. (2012). The recommended process route entails that base metals (BMs) are leached from the ore with 10 g/l sulphuric acid and thermophilic micro-organisms (primarily *Sulfolobus metallicus* and *Metallosphaera sedula*) in a primary heap bioleach, after which the PGM values are recovered from the bioleach solid residue in a second-stage cyanide heap leach (Mwase, 2009; Mwase et al., 2012). Ferrous iron has to be fed to the heap at a concentration of 2 g/l in addition to the sulphuric acid and micro-organisms as the leaching of metals from the ore is catalysed by iron-oxidizing bacteria.

The resulting bioleach solution exits the heap at 65°C in the pH range of 0.8-1.2. The expected concentrations of the dissolved metals in the leach solution, as presented by Liebenberg et al. (2013), are: 690 ppm Cu, 974 ppm Ni, 267 ppm Fe (after Fe removal by hydroxide precipitation), 776 ppm Al, 34 ppm Co, 16 ppm Zn, and 27 ppm Mn. The initial treatment steps of the leach solution, which entail the removal of iron and the recovery of copper, have been described by Liebenberg et al. (2013). It was proposed that hydroxide precipitation be used to remove iron from solution, after which copper can be recovered completely by means of ion exchange and split elution with Dow XUS43605 as resin (Liebenberg et al., 2013). The leach solution recovered after iron precipitation and copper ion exchange contained primarily Ni and Al as well as low concentrations of Co, Fe, Zn, and Mn. The composition of the synthetic bioleach solution used in this study is presented later in this paper.

### Theory

A wide range of resins are commercially available that could potentially be used for nickel and cobalt adsorption. The most common functionalities are bispicolylamine (Bis-PA) and iminodiacetic acid (IDA). It is known that difficulties are encountered in the elution of copper from Bis-PA resins. Copper and iron furthermore load preferentially onto IDA-type resin, which reduces the resin's capacity for nickel and cobalt loading and hence limits the upgrading of these metals of interest. For these reasons, copper and iron have to be removed from the solution prior to using these resins for the recovery of nickel and cobalt from the leach solution (Sirola *et al.*, 2008; Sirola *et al.*, 2010). The dependence of the stability constants of metals complexation with bispicolylamine on pH is illustrated in Figure 1 (Sirola *et al.*, 2008).

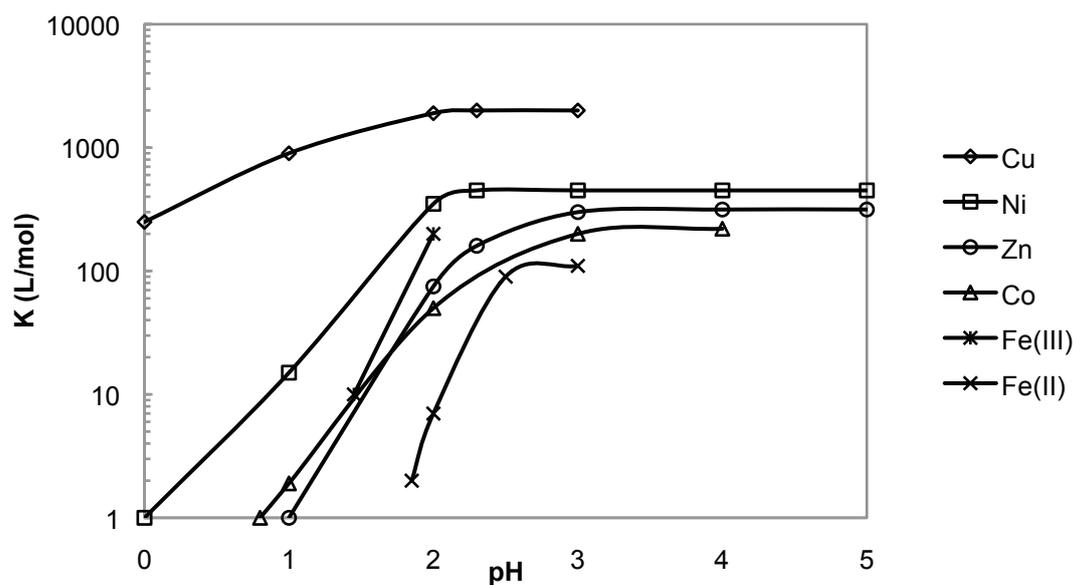


Figure 1. Stability constants of complexation of transition metal ions with Dow M4195 as a function of pH (Sirola *et al.*, 2008)

The selectivity of an ion exchanger is dependent on various factors including the conditions of polymerization, solution composition, solution pH, as well as the type of ligand or functional group attached to the resin (Nicol, 2003; Sirola, 2009). Amongst these, the type of ligand has the greatest influence on a resin's selectivity (Sirola, 2009).

The use of Dow M4195 for nickel and cobalt recovery has been widely studied and the effects of operating conditions such as solution pH and flow rate on nickel and cobalt recovery are well understood (Grinstead, 1984; Rosato *et al.*, 1984; Mendes and Martins, 2004; Sirola *et al.*, 2008). The effect of temperature on the recovery of nickel and cobalt with Dow M4195 has been studied to a lesser extent, which motivated the inclusion of this parameter in this study.

Dow M4195 consists of the bispicolylamine ligand supported by a polymeric backbone of styrene (St) cross-linked with divinylbenzene (DB). Metal complexation with Dow M4195 is shown in Figure 2. The metal ion acts as a Lewis acid (as it accepts electrons) and the chelating ligand acts as a Lewis base (as it donates electrons) in the adsorption of metal ions by bispicolylamine (Irving and Williams, 1953; Pearson, 1963; Sirola, 2009).

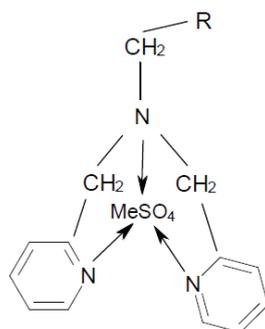


Figure 2. Metal complexation with Dow M4195

The objectives of this study were to determine the equilibrium and kinetic parameters of nickel and cobalt adsorption with Dow M4195, and to determine the effects of operating conditions (initial solution pH, feed flow rate, temperature, and initial metals concentration) on metal adsorption during the continuous recovery of the metals of interest.

## Experimental

### Materials

The reagents that were used for the preparation of the synthetic bioleach solution and the eluting agents are listed in Table I along with their respective purities. All the chemicals were supplied by Kimix.

**Table I. List of chemicals**

Reagent	Purity/concentration
CuSO <sub>4</sub> ·5H <sub>2</sub> O	99-100%
NiSO <sub>4</sub> ·6H <sub>2</sub> O	99-100%
CoSO <sub>4</sub> ·7H <sub>2</sub> O	99-100%
ZnSO <sub>4</sub> ·7H <sub>2</sub> O	99-100%
Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ·10H <sub>2</sub> O	99-100%
FeSO <sub>4</sub> ·H <sub>2</sub> O	99-100%
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ·18H <sub>2</sub> O	99-100%
MnSO <sub>4</sub> ·4H <sub>2</sub> O	99-100%
NaOH	99-100%
H <sub>2</sub> SO <sub>4</sub>	95-98%
HNO <sub>3</sub>	55%
NH <sub>3</sub> solution	33%
HCl	37%

The chelating resin used in this work, Dow M4195, is a macroporous poly-styrene divinylbenzene resin with bispicolylamine functionality. The resin particle size varies between 300 μm and 850 μm. In order to allow comparison of Dow M4195 with resins with other functionalities, Dow XUS43605 (hydroxypropylpicolylamine functionality) and Amberlite IRC748 (IDA functionality) were also tested for the recovery of nickel and cobalt. A summary of the details of the resins used in this study is presented in Table II.

**Table II. Commercially available IX polymeric resins for the selective adsorption of copper, nickel, and cobalt investigated in this study**

Resin	Manufacturer	Functionality	Matrix
Dow M4195	Dow Chemical Company	Bis-PA	Macroporous St-DB
Dow XUS43605	Dow Chemical Company	HPPA	Macroporous St-DB
Amberlite IRC748	Rohm and Haas	IDA	Macroporous St-DB

## Methods

### Pre-treatment of resins

The resins listed in Table II were pre-treated by packing particles into glass columns with sintered bottoms and washing with 10 BV of distilled water at a flow rate of 10 BV/h to remove solid particles and impurities originating from the polymerization process. Thereafter the resins were washed with 10 BV of 1M H<sub>2</sub>SO<sub>4</sub> at a rate of 5 BV/h to ensure that the resin was protonated. The resins were washed again with 10 BV of distilled water to remove excess acid, before being removed from the column. Excess water was removed from the washed resin using filtration and the resin was stored in the container that it was supplied in.

### Preparation of synthetic bioleach solution

The composition of the pregnant bioleach solution is based on the work of Liebenberg *et al.* (2013). Given the conclusion by Liebenberg *et al.* that complete copper removal is possible using Dow XUS43605, copper was omitted from the synthetic leach solution used in this study. The effluent from the copper recovery section therefore has a composition as reported in Table III.

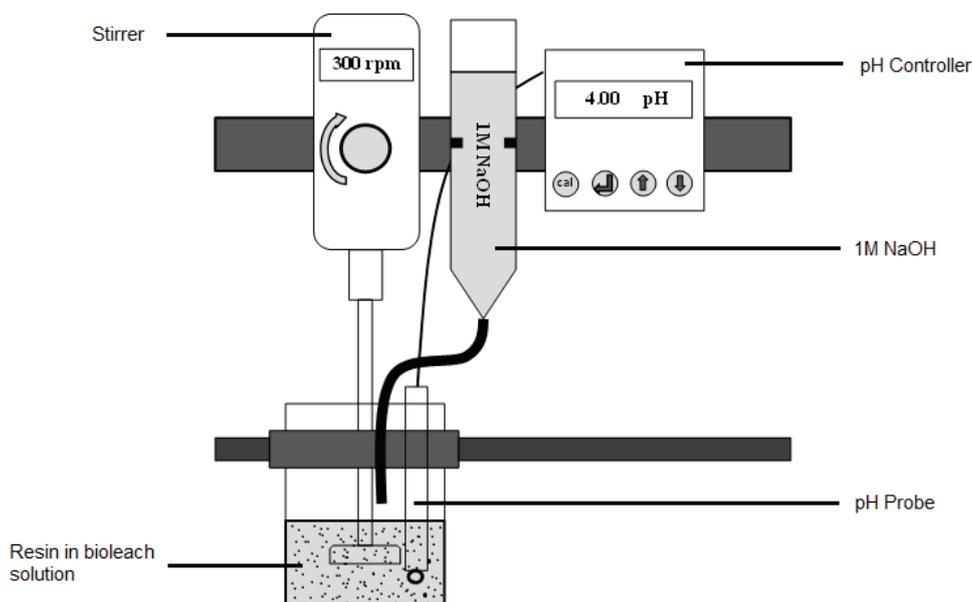
**Table III. Composition of the feed bioleach solution**

Metals concentration (ppm)					
Ni	Co	Fe	Zn	Mn	Al
974	34	267	16	27	776

The correct amounts of the respective metal salts, with the exception of iron, were dissolved in water to prepare the synthetic bioleach solution with the composition shown in Table III. Ferric iron was dissolved in 1M H<sub>2</sub>SO<sub>4</sub> before it was added to the solution containing the other metals. The pH of the solution was raised to the pH required for subsequent tests by the addition of concentrated NaOH. Precipitate that formed as a result of the increased pH was allowed to settle out overnight, after which the clarified solution was separated from the precipitate for use in the experiments.

### Resin screening

The suitability of the resins listed in Table II to adsorb nickel and cobalt selectively from the solution was determined in screening tests. In these tests, the different resins were contacted with synthetic solution in stirred beakers at a ratio of 1:50 and initial solution pH values of 3 and 4 for 48 hours to ensure that equilibrium had been established. At the end of the 48 hour period, samples were withdrawn from the beakers for analysis. The experimental set-up is illustrated in Figure 3.



**Figure 3. Experimental set-up for batch experiments**

### Batch kinetic and equilibrium adsorption

The set-up in Figure 3 was also used for batch kinetic and equilibrium experiments. For the batch kinetic experiments, pre-treated Dow M4195 was contacted with the synthetic solution at a ratio of 1:50. The pH of the solution was maintained at a desired value by adding 1M NaOH dropwise to the beaker using an automatic pH controller. Samples of

the solution were withdrawn from the beakers at various time intervals over a 24 hour period to be analysed. For the batch equilibrium experiments, Dow M4195 was contacted with synthetic solution at various ratios ranging from 1:5 to 1:100. For each ratio tested, a sample of the solution phase was taken after 48 hours for analysis.

#### *Dynamic column adsorption*

10 mL of tapped resin was placed in each of the glass columns with sintered bottoms and water jackets. A peristaltic pump was used to pump the synthetic solution from a temperature-controlled reservoir into the columns, which were maintained at the same temperature as the reservoir. Samples of the barren solution were collected at the bottom of the each column for analysis. A schematic illustration of the experimental set-up is shown in Figure 4.

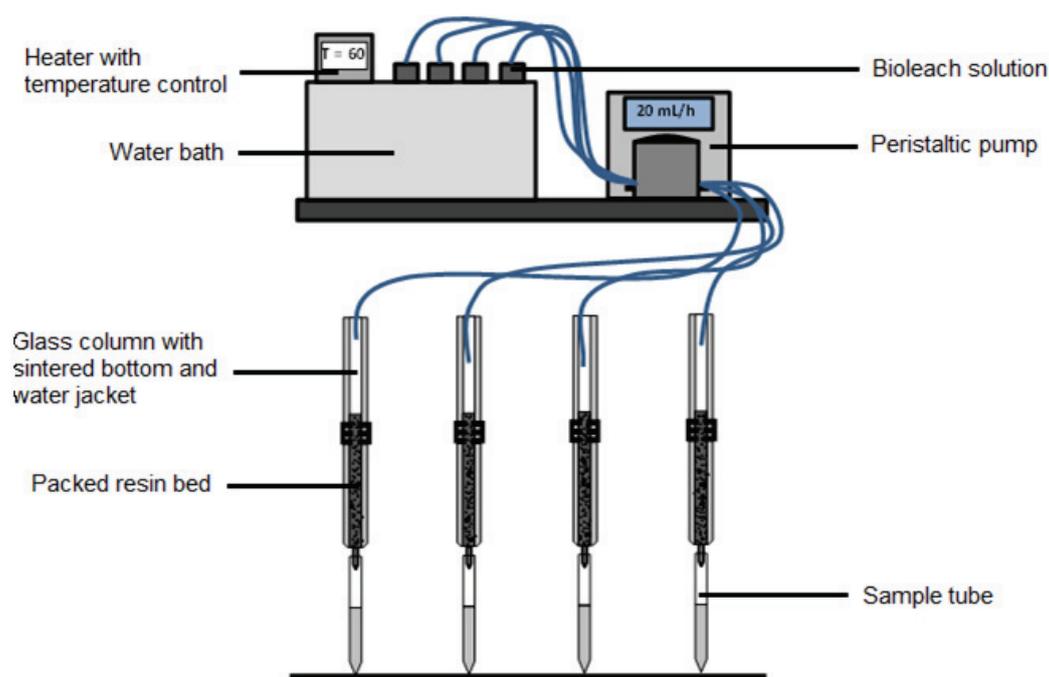


Figure 4. Experimental set-up for dynamic column adsorption and elution experiments

#### *Column elution*

The set-up in Figure 4 was also used for column elution experiments. Dow M4195 was loaded at a flow rate of 5 BV/h, a temperature of 60°C, and an initial solution pH of 4. After loading the resin in separate batches, it was mixed to achieve a homogeneously loaded resin that was used in column elution experiments. The resulting metals loading on the resin was as follows: 18.1 g/l nickel, 355 ppm cobalt, 114 ppm iron, 52 ppm zinc, and less than 5 ppm manganese and aluminium. 10 mL of the loaded resin was packed into the glass columns and the metals on the resin were eluted by pumping H<sub>2</sub>SO<sub>4</sub> through the packed resin bed using a peristaltic pump at the desired flow rate. Samples of the eluate were collected at the bottom of each column for analysis.

#### *Analysis*

Flame atomic absorption spectroscopy (AAS) was used to analyse for the concentrations of the metals in the synthetic bioleach solutions and all barren solutions. All iron concentrations refer to the total iron concentration in solution, as the relative concentrations of ferrous and ferric ions were not analysed.

## **Results**

#### *Resin screening*

The suitability of the resins listed in Table II to recover nickel and cobalt from the bioleach solution was tested in screening experiments. The separation factors of nickel, cobalt and iron for the various resins are listed in Table IV. The separation factor, defined as the ratio of the distribution of one metal ion between the resin phase and the solution phase

to that of another metal ion, is calculated according to Equation [1]. Subscripts A and B refer to metal cations, and s and r refer to the solution phase and resin phase respectively. Both the feed and the final solutions were analysed to determine the concentration of the respective species in the respective phases.

$$\alpha_B^A = \frac{D_A}{D_B} = \frac{C_{A,r}C_{B,s}}{C_{A,s}C_{B,r}} \quad [1]$$

**Table IV. Separation factors of nickel, cobalt, and iron for the respective resins at different pH values**

Resin	pH 2			pH 3			pH 4		
	$\alpha_{Co}^{Ni}$	$\alpha_{Fe}^{Ni}$	$\alpha_{Fe}^{Co}$	$\alpha_{Co}^{Ni}$	$\alpha_{Fe}^{Ni}$	$\alpha_{Fe}^{Co}$	$\alpha_{Co}^{Ni}$	$\alpha_{Fe}^{Ni}$	$\alpha_{Fe}^{Co}$
Dow M4195	350	26.8	0.076	262	41.8	0.160	84.3	65.4	0.776
Dow XUS43605	42.6	4.3	0.102	16.6	1.4	0.084	5.1	3.2	0.628
Amberlite IRC748	0.489	0.011	0.022	6.2	0.064	0.010	4.8	0.822	0.172

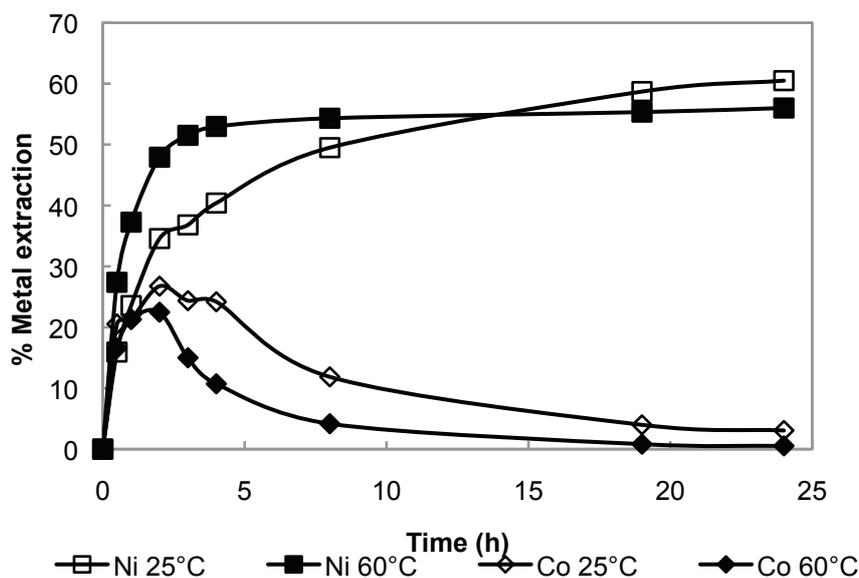
The results of the screening tests indicated that Dow M4195 exhibited the highest selectivity towards nickel over cobalt and towards nickel over iron at all pH values investigated. While all the resins are more selective for iron than for cobalt, Dow M4195 showed the highest selectivity towards cobalt over iron at pH values of 3 and 4. This resin was therefore selected for the recovery of nickel and cobalt.

#### Kinetics of adsorption

The rates of nickel and cobalt loading onto Dow M4195 at 25°C and 60°C are illustrated in Figure 5, and the equilibrium loadings of the respective metals are summarized in Table V.

**Table V. Equilibrium loadings of metals on Dow M4195 at 25°C and 60°C**

Temperature °C	Metals loading at equilibrium (g/l)					
	Ni	Co	Fe	Zn	Mn	Al
25	26.95	0.043	0.053	0.033	0	0
60	24.95	0.0075	0.028	0.023	0	0

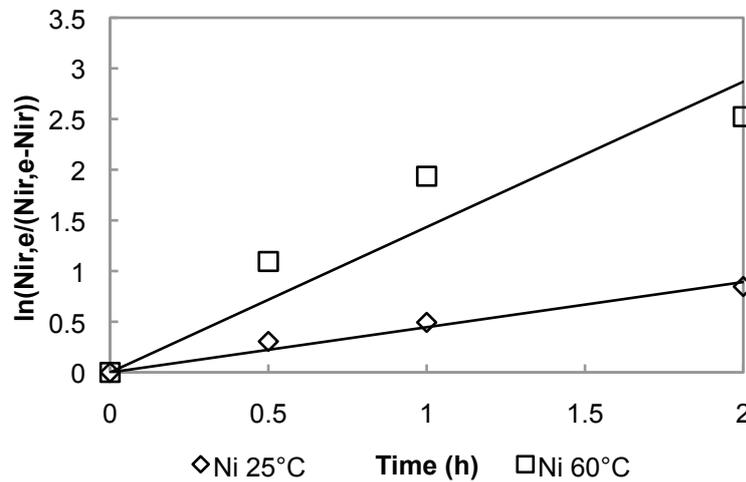


**Figure 5. Kinetics of nickel and cobalt adsorption onto Dow M4195 from the multicomponent bioleach solution at 25°C and 60°C**

To determine the initial rates of nickel adsorption onto Dow M4195 at 25°C and 60°C,  $k_{25^\circ\text{C}}$  and  $k_{60^\circ\text{C}}$ , a first-order approach to equilibrium kinetic model was used, as shown in Figure 6. The rate constants of nickel adsorption at 25°C and 60°C are reported in Table VI. The rate of approach to nickel adsorption equilibrium increased as the temperature increased from 25°C to 60°C, while the equilibrium loading of nickel did not change significantly for this increase in temperature (Table V). The lower viscosity of the leach solution at the higher temperature resulted in improved intraparticle mass transfer and hence the increased rate constant at 60°C. The observed effect of temperature on the loading kinetics agrees with the study by Sirola *et al.* (2010), who reported that the rate of nickel adsorption onto silica-supported 2-(aminomethyl)pyridine increased with increasing temperature in the range of 25–90°C.

**Table VI. First-order nickel adsorption rate constants at 25°C and 60°C**

Temperature (°C)	First-order rate constant (h <sup>-1</sup> )	R <sup>2</sup>
25	0.446	0.97
60	1.434	0.86



*Figure 6. Determination of first-order approach to equilibrium rate constants for Ni adsorption onto Dow M4195*

The activation energy of nickel adsorption with Dow M4195 was calculated from the initial adsorption rates reported in Table VI at 25°C and 60°C using the Arrhenius equation (Equation [2]).

$$k_T = A \exp\left(-\frac{E_a}{2.303RT}\right) \quad [2]$$

In Equation [2],  $k_T$  refers to the first-order nickel adsorption rate constant at temperature T, A is the pre-exponential factor,  $E_a$  represents the activation energy of the nickel adsorption reaction, and R is the universal gas constant. By linearizing Equation 2, the activation energy of nickel adsorption was calculated to be 63.43 kJ/mol.

#### **Equilibrium adsorption isotherms**

Equilibrium isotherms were constructed by contacting the resin and synthetic bioleach solution at resin to solution ratios of 1:5, 1:15, 1:30, 1:50, 1:75, 1:100, and 1:120 at room temperature. Langmuir and Freundlich isotherm models (Equation [3] and Equation [4] respectively) were fitted to the equilibrium data. The results are shown in Figure 7.

$$Q_r = \frac{Q_{r,max} C_s b}{Q_{r,max} + b C_s} \quad [3]$$

$$Q_r = A(C_s)^{\frac{1}{n}} \quad [4]$$

In Equation [3] and Equation [4],  $Q_r$  and  $C_s$  refer to the concentration of the metal on the resin and in the solution respectively, while  $Q_{r,max}$  and  $A$  refer to the maximum loading capacity of the resin. The coefficient  $b$  is an adsorption equilibrium constant which is a direct measure of the adsorption intensity, and  $1/n$  is a measure of adsorption intensity or surface heterogeneity.

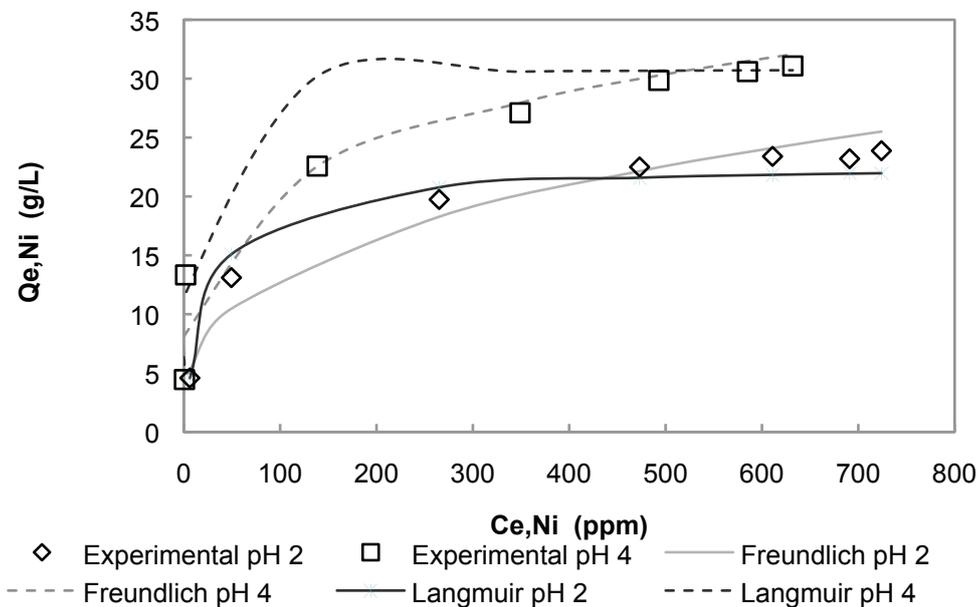


Figure 7. Nickel adsorption isotherms for Dow M4195 at solution pH values of 2 and 4

The parameters in the models in Equation [3] and Equation [4] are reported in Table VII. In each case the Langmuir isotherm model provided a better fit for the experimental data, yielding fits with  $R^2$  values of 0.995 and 0.97 at pH values of 2 and 4 respectively, compared to the Freundlich isotherm model, which yielded  $R^2$  values of 0.96 and 0.86 at pH values of 2 and 4 respectively. The apparent decrease in the maximum loading capacity of the resin at lower pH values can be ascribed to the larger degree of functional group protonation for the more acidic solutions.

Table VII. Parameters of Langmuir and Freundlich models for nickel binding with Dow M4195

Parameter	pH 2		pH 4	
	Langmuir	Freundlich	Langmuir	Freundlich
$Q_{r,max}$	22.72	-	30.86	-
$b$	40	-	324	-
$A$	-	28.38	-	35.66
$1/n$	-	0.3316	-	0.232
$R^2$	0.995	0.96	0.97	0.86

**Column adsorption**

*Effects of operating conditions on metal breakthrough profiles*

The effects of flow rate (2.5 BV/h, 5 BV/h, and 7.5 BV/h), temperature (25°C and 60°C), pH (2 and 4), and initial metal concentrations on metal breakthrough profiles were studied in dynamic column adsorption experiments. Figure 8 and Figure 9 illustrate the effects of flow rate on nickel and cobalt breakthrough profiles at 25°C and 60°C respectively.

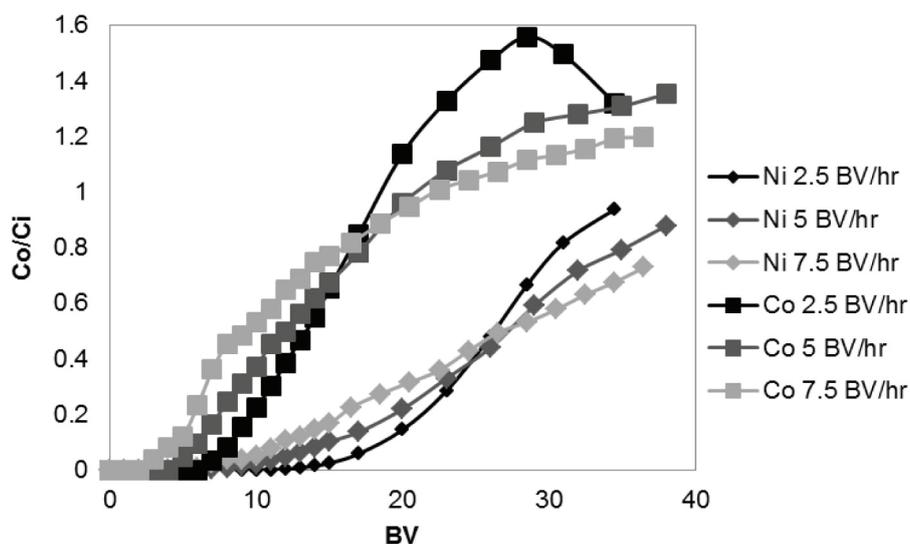


Figure 8. Effect of flow rate on nickel and cobalt breakthrough profiles for Dow M4195 at 25°C and an initial solution pH of 4

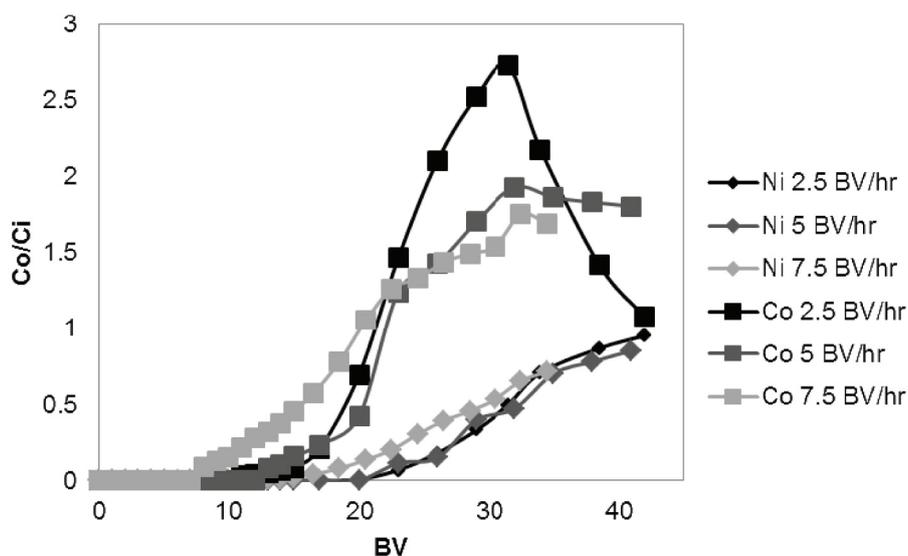


Figure 9. Effect of flow rate on nickel and cobalt breakthrough profiles for Dow M4195 at 60°C and an initial solution pH of 4

The effect of increasing the flow rate from 2.5 BV/h to 7.5 BV/h could be seen as a result of the slow rate at which metal adsorption with Dow M4195 attains equilibrium. The loading of nickel and cobalt on the resin at 1% breakthrough decreased from 16.07 g/l and 319 ppm to 9.18 g/l and 273 ppm, respectively when the flow rate was increased from 2.5 to 5 BV/h at 25°C. The concentrations of these metals on the resin at 1% breakthrough decreased further to 6.88 g/l and 150 ppm when the flow rate was increased from 5 BV/h to 7.5 BV/h at 25°C. As expected, increasing the flow rate also resulted in an increased mass transfer zone height.

Due to the increased rate of metal adsorption at 60°C compared to 25°C, initial breakthrough of nickel and cobalt occurred at a higher BV at 60°C, and thus the loadings of these metals on the resin were higher when breakthrough occurred at 60°C. These results illustrate the advantage of operating at an elevated temperature: although the resin capacity is lower at 60°C than at 25°C, increasing the temperature allows operation at higher flow rates as higher nickel and cobalt loadings on the resin at breakthrough are achievable at 60°C than at 25°C at the same flow rates. The nickel loading on the resin at 1% nickel breakthrough increased from 9.18 g/l to 21 g/l at a flow rate of 5 BV/h when the temperature was increased from 25°C to 60°C (Figure 10 provides an indication of the increased metal loading at breakthrough). The cobalt loading at breakthrough increased from 319 ppm to 487 ppm for the same increase in

temperature. For the conditions investigated, the mass transfer zone height also decreased when the temperature was increased from 25°C to 60°C.

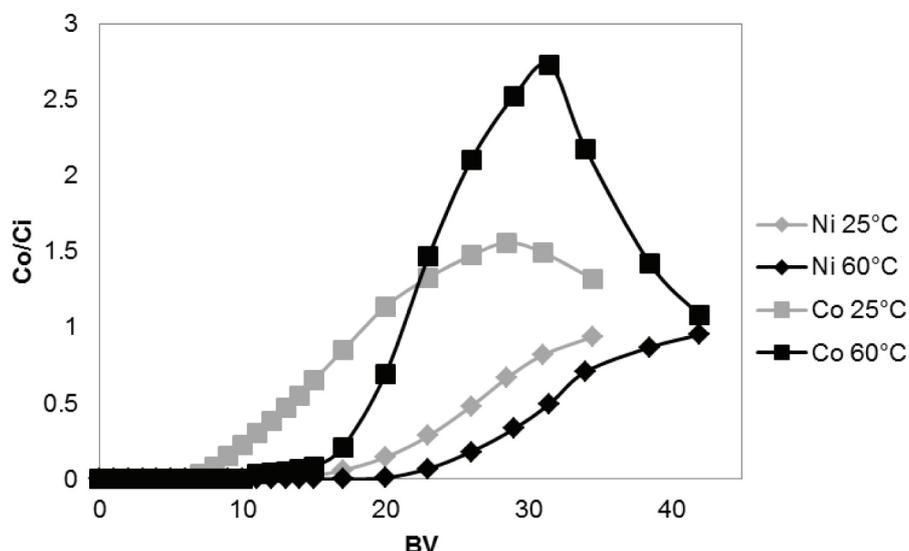


Figure 10. Effect of temperature on Ni and Co breakthrough profiles for Dow M4195 at a flow rate of 2.5 BV/h and an initial solution pH of 4

Statistical analysis of metal breakthrough data

The statistical significance of the effects of temperature, flow rate, solution pH, and initial metals concentration on the operating capacity of this resin was determined by performing linear regression. The nickel and cobalt (referred to as target metals, the concentrations of which are indicated as [TM]<sub>s</sub>) loadings on Dow M4195 at 1% nickel breakthrough were considered as the response variables. Considering the p-values reported in Table VIII, the effects of flow rate and temperature were found to be the most significant, followed by the initial concentration of target metals in the solution. The interaction parameters that were found to be significant were the interaction between flow rate and temperature, flow rate and initial target metals concentration in the solution, and temperature and gangue metals concentration in solution (indicated as the concentration of other metals, [OM]<sub>s</sub>). The half-normal probability plot shown in Figure 11 and the main effects plot in Figure 12 confirmed that the effect of temperature was the most significant, and that an increase in temperature resulted in an increase in the target metals loading on the resin at nickel breakthrough. As expected, an increase in the flow rate and initial gangue metals concentration resulted in a decrease in the target metals loading achieved on the resin at nickel breakthrough.

Table VIII. p-values of main effects influencing the target metal loading on Dow M4195 at nickel breakthrough

Flow rate	Temperature	p-values			
		[TM] <sub>s</sub>	F-T	F-[TM] <sub>s</sub>	T-[OM] <sub>s</sub>
< 0.0001	< 0.0001	0.013	0.0086	0.18	0.20

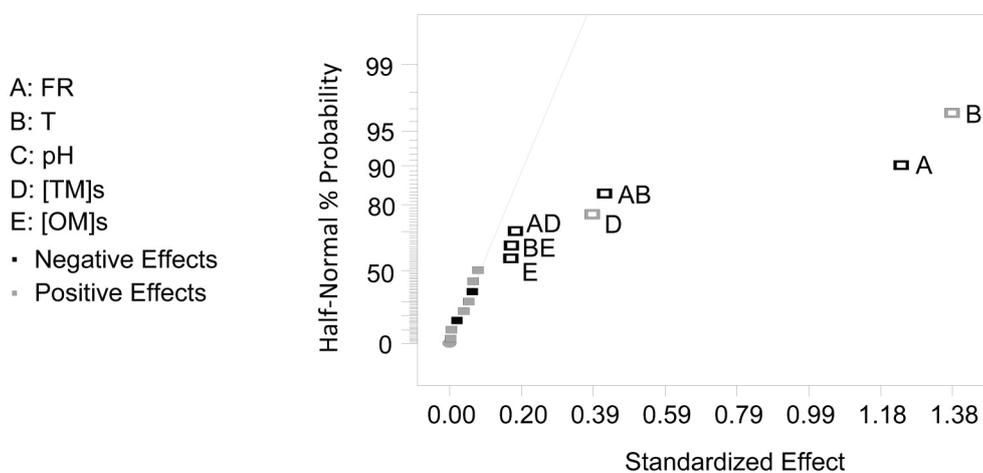


Figure 11. Half-normal probability plot indicating the significance of the main effects on the target metal loading on Dow M4195 at Ni breakthrough

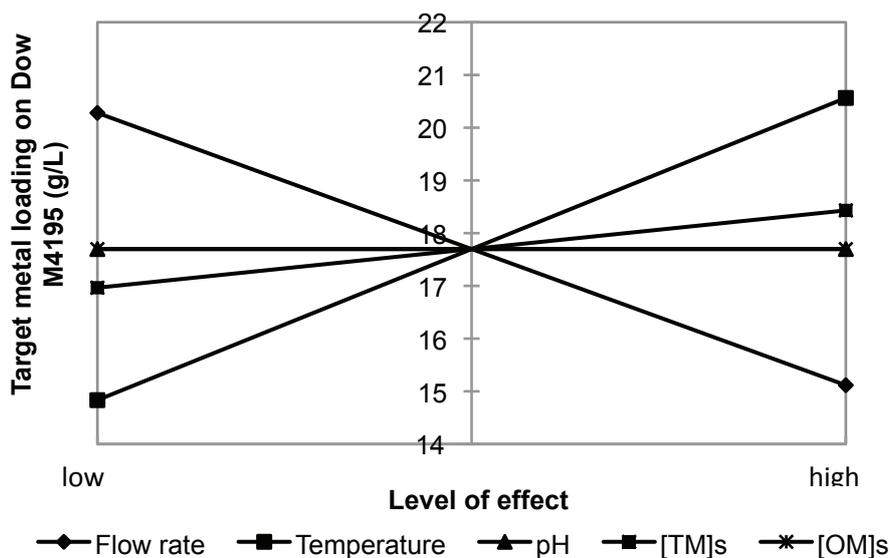


Figure 12. Effects of main parameters on the target metal loading on Dow 4195 at Ni breakthrough

The normalized regression model that was obtained (Equation [5]) yielded an adjusted  $R^2$  value of 0.97.

$$[TM]_r = -0.6F + 0.7T + 0.2[TM]_s - 0.1[OM]_s - 0.2FT - 0.1F[TM]_s - 0.1T[OM]_s \quad [5]$$

**Column elution**

Dow M4195 was loaded at a flow rate of 5 BV/h, an initial solution pH of 4 and a temperature of 60°C in column configuration. The concentrations of different transition metal ions on the loaded resin are reported in Table IX.

**Table IX. Metal loading on Dow M4195**

Metal concentration (ppm)					
Ni	Co	Fe	Zn	Mn	Al
18079	355	114	52	<5	<5

The possibility of performing a split elution was investigated by eluting Dow M4195 with various H<sub>2</sub>SO<sub>4</sub> concentrations (20 g/l, 100 g/l, and 200 g/l). The effects of acid concentration and temperature on nickel elution and on cobalt elution from Dow M4195 are illustrated in Figure 13 and Figure 14 respectively. Elution was carried out at a flow rate of 10 BV/h.

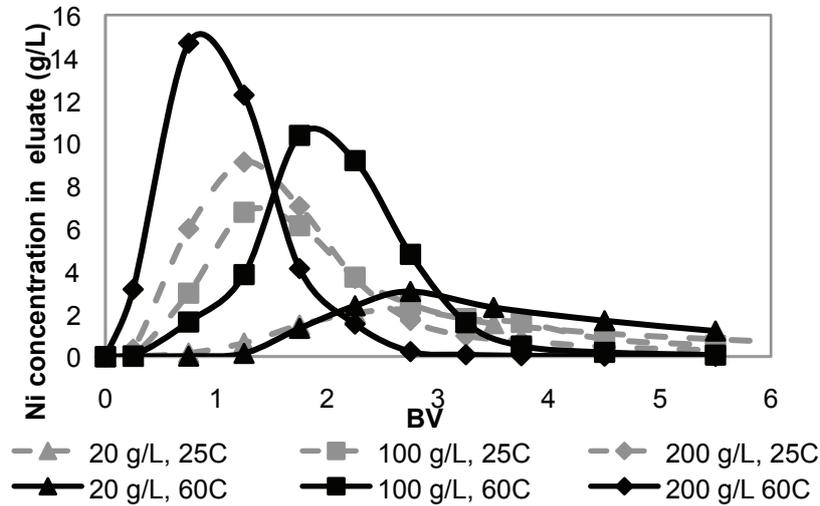


Figure 13. Effects of H<sub>2</sub>SO<sub>4</sub> concentration and temperature on nickel elution from Dow M4195

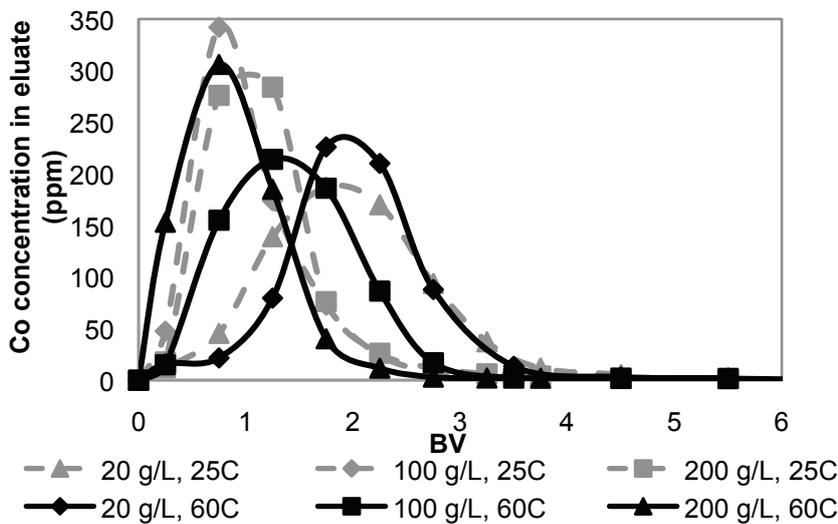


Figure 14. Effects of H<sub>2</sub>SO<sub>4</sub> concentration and temperature on cobalt elution from Dow M4195

Figure 13 and Figure 14 indicate that the rate of nickel and cobalt elution increased with increasing H<sub>2</sub>SO<sub>4</sub> concentration and temperature. Nickel was completely eluted with 2-3 BV of 200 g/l H<sub>2</sub>SO<sub>4</sub> at 60°C, while cobalt was completely eluted with 3-4 BV of 20 g/l H<sub>2</sub>SO<sub>4</sub> at the same temperature. A split elution could therefore be carried out to remove the majority of the cobalt loaded on the resin with dilute acid, after which a nickel-rich eluate could be obtained by eluting the remainder of metals on the resin with 200g/l H<sub>2</sub>SO<sub>4</sub>.

### Conclusions

This study investigated the use of Dow M4195, a bispicolyamine-type resin, for the selective recovery of nickel and cobalt from a multicomponent bioleach solution. Screening experiments indicated that the resin has sufficient

selectivity towards nickel and cobalt in order to selectively recover these species from the bioleach solution, and that the resin has superior iron rejection compared to IDA-type resins.

The rate of nickel adsorption equilibrium attainment increased with increasing temperature. The maximum nickel loading capacity of Dow M4195 was determined to be 22.72 g/l and 30.86 g/l at pH values of 2 and 4, respectively.

Dynamic column adsorption experiments showed that the effects of temperature and flow rate, in this specific order, on the nickel and cobalt loadings on Dow M4195 at initial nickel breakthrough were the most significant. At a flow rate of 5 BV/h and initial solution pH of 4, an increase in temperature from 25°C to 60°C resulted in a 105% increase in the nickel loading on the resin at 1% nickel breakthrough.

Finally, it was determined that it is possible to perform a split elution by selecting the appropriate H<sub>2</sub>SO<sub>4</sub> concentrations and operating conditions. It was found that nearly complete cobalt elution could be achieved with 3.5 BV of 20 g/l H<sub>2</sub>SO<sub>4</sub> at a flow rate of 10 BV/h and a temperature of 60°C, while only 27% nickel is eluted in the same fraction. A nickel-rich eluate could then be obtained by treating the resin with 3.5 BV of 200 g/l H<sub>2</sub>SO<sub>4</sub>.

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