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OPTIMIZING THE OPERATING CONDITIONS OF GOLD ELUTION AND ELECTROWINNING FOR TAU LEKOA STREAM AT KOPANANG GOLD PLANT

Alfred Lodi Lunga

A research report submitted to the School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Master of Science in Engineering

Johannesburg, 2006

DECLARATION

I declare that this research report is my own work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree at any other university.

……

14th day of December 2006

ABSTRACT

The final gold product of Tau Lekoa mine has a low fineness. This is caused by high concentration of bases metals in the reefs. Some of these base metals together with gold are leached with cyanide and are loaded into carbon. If not adequately controlled, they may elute with gold and contaminate the final product in the electrowinning process.

Based on the understanding of the kinetics of the elution, four parameters, namely temperature, flow rate, free caustic soda concentration and cyanide strength, were evaluated first for the elution process. Experimental runs on the plant scale did prove that the first three parameters are the predominant parameters that maintain base metals in the carbon during the elution and therefore assist in the improvement of the fineness of the final product. Recommendations were made to change the operating conditions and the fineness of the gold did improve from 80% to 84 %.

In addition, a thermodynamic model that took to consideration the competition of gold and nickel was developed for the electrowinning process. This model showed that the deposition of gold and nickel during the electrowinning was dependant of their concentrations and temperature.

The single pass efficiencies and the deposition rates were also tracked during the experimental.

Based on the finding on the reduction of electrowinning time, the fineness of the final product was improved from 84% to 85%.

As the refining cost depends on the fineness of gold, the improved fineness means that the gold content in the bullion is increased and the impurities are decreased, therefore, the refining cost will decrease as lower penalty costs are charged for the treatment of the bullion with high fineness.

The recommendations of the changes have been implemented permanently and these did show permanent improvement of the fineness.

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CHAPTER 1 INTRODUCTION

1.1 Background

Tau Lekoa Mine is wholly owned by Anglogold Ashanti and is situated on the Vaal River, North West Province. The mine produces around 450 kg of gold a month. The ores from the mine are treated in a separate stream at Kopanang Gold Plant.

The Kopanang Gold Plant is a modern plant that uses mill-leach-CIP- electrowinning processes. The gold from the electrowinning process is smelted centrally in another plant situated 5 km away from Kopanang. The quality of the final bullion is affected by the presence of base metals. This project focuses on the assessment of the existing operating parameters particularly with regards to elution and electrowinning processes and recommends changes in order to improve the fineness of the product.

1.2 Problems

The reefs from Tau Lekoa underground mines contain low grade gold (2-3 g/t) and they are characterized by the presence of base metals like nickel, copper, zinc and cobalt. Although the concentrations of these base metals are very low, they have a negative impact on the downstream operations.

In order to obtain the required throughput of the plant during the mill stage, more steel balls are added. The steel consumption is 1 kg per ton of ore. This causes the iron content to increase in the circuit and get deposited with other base metals in the final product if the elution and electrowinning processes are not well controlled.

The base metals tend to leach out in cyanide and are loaded on the carbon. Adsorbed base metals in the CIP can be stripped together with gold in the elution process. Depending on their concentration in the pregnant solution, cathodic deposition occurs.

Base metals that have not been stripped during the elution will build up in the carbon and will affect the gold loading in the CIP process.

The continuous decrease of gold content in the stream and the variability of flow rate and temperature affect the elution and electrowinning processes. Low-grade eluate tends to be problematic for electrowinning as the impurities tend to “compete “with the gold for deposition current.

1.3 Tau Lekoa Elution and Electrowinning process description

1.3.1 Elution Circuit

Figure 1 shows a flow sheet of the elution circuit. The elution column operates with a 2-2.5% NaOH solution with a temperature range of 120^{o}C-135^{o}C. The gold is stripped from the carbon into the solution. An elution will start when there is 6 ton of loaded carbon in the measuring vessel.

The caustic solution that returns from the electrowinning circuit is pumped into the eluant tanks. This solution is sent through a primary heat exchanger where the heat from the exiting solution of the column is used to preheat the entering solution. It is then sent through a steam heater which raises the temperature to the required range.

The caustic solution is circulated through the elution column. Eluant enters at the bottom and eluate leaves at the top through the outlet. This pregnant solution goes to the electrowinning where it passes through the cells. The eluant is pumped to the eluant tanks and from there it is circulated back to the elution columns.

The process is slow with a residence time of 17-20 hours for satisfactory elution.

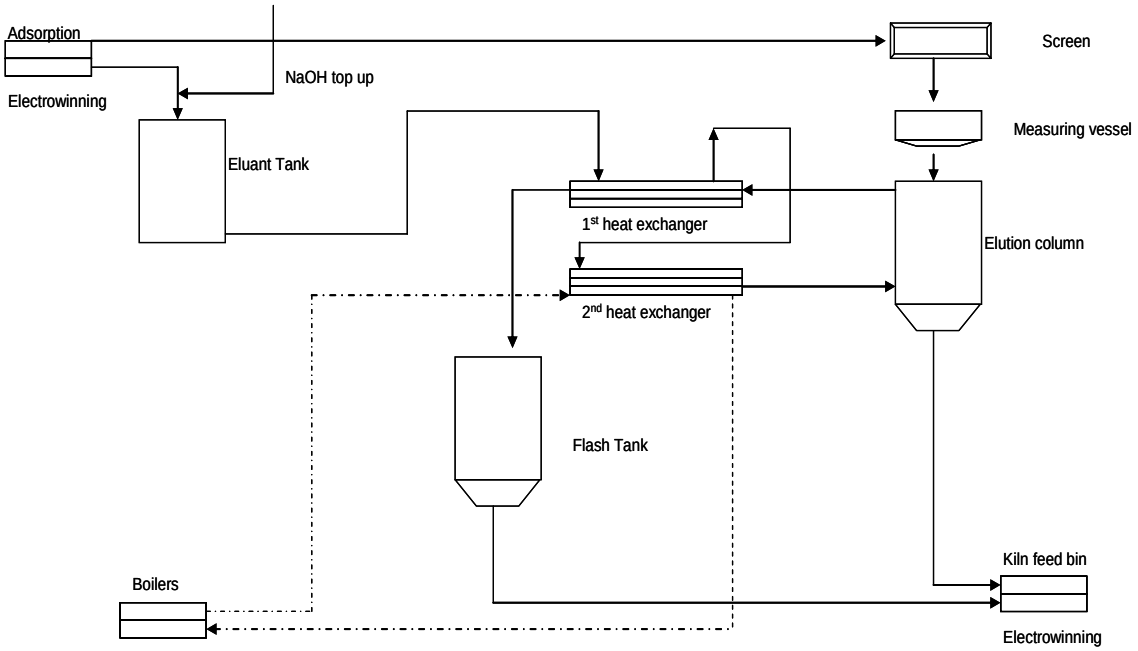


Figure 1 Elution circuit

1.3.2 Electrowinning

The electrowinning circuit is shown in Figure 2. The pregnant solution flows from the flash tank to the electrowinning cells. A current is passed through the cells from a set of rectifiers. The gold is attracted to the cathodes and electroplates onto it. The cathodes are called baskets and consist of stainless steel mesh to increase the surface area exposed to the plating process. These baskets are removed once the plating is done and washed with water under high pressure. The particulate concentrate is passed to a filter press where it is collected and weighed. Final product is the concentrate which is stored in bins, which are sealed and dispatched, to the central smelt-house. The gold barren solution is pumped to the eluant tanks for the next elution.

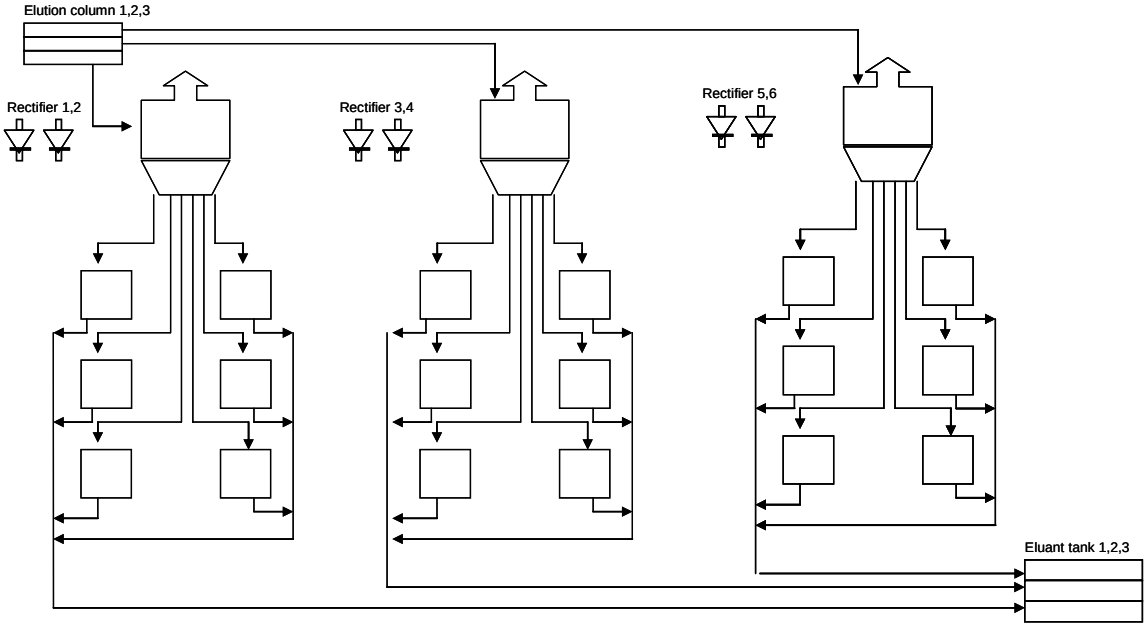


Figure 2 Electrowinning circuit

1.4 Zadra process description

Tau Lekoa stream uses the Zadra process. The eluant is continuously circulated through the column and an electrowinning cell in series. A caustic cyanide solution, normally 0.2 to 0.5 % NaCN and 2% NaOH, is pumped to the elution column and is pre-heated by the solution leaving the column. The temperature is further raised by a steam heat exchanger. After stripping the gold from the carbon, the solution is partially cooled in the incoming heat exchanger and further cooled to below its ambient boiling point in a cooler heat exchanger. The gold is then stripped from the solution by electrowinning and the solution is returned to the elution column.

Build-up of contaminants may be prevented by discarding part or all the eluant and replacing it with fresh solution. A simplified process flow sheet is given in Figure 3

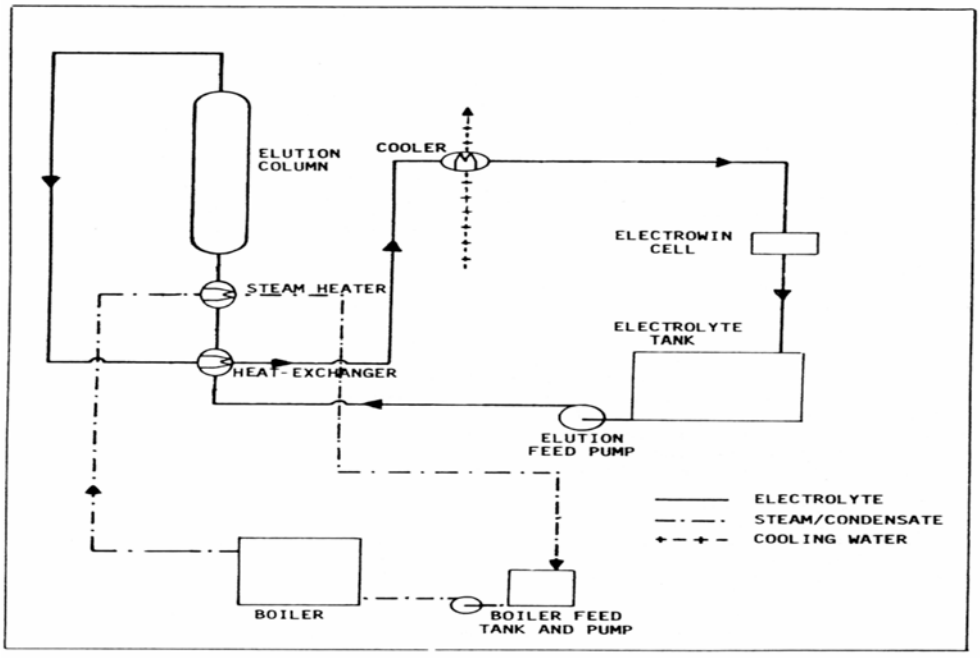


Figure 3 Zadra Elution process

1.5 Project Aims

The specific objectives of the project are to:

- Understand the kinetics of the elution and electrowinning circuits and the impact of different base metal elements specifically nickel.
- Establish the operating conditions that will improve the fineness of the gold bullion, therefore reduce its refining cost as it will contain fewer impurities.
- Modeling the gold cathodic reactions and establishment of the operating conditions that will improve the quality of the final gold product.

1.6 Organization of the research report

The first chapter describes the Tau-Lekoa Mines, which is part of Anglogold Ashanti. It introduces the problems that cause the fineness of final bullion to be low. The quality of gold is contaminated by base metals that are coming from the ores. This chapter concludes with the description of the elution and electrowinning processes at the Kopanang Plant. The description of the Zadra process and the aims of the project are also given in the chapter.

The second chapter reviews the literature on the kinetics and thermodynamics of elution and electrowinning of gold. It shows how the base metals, if not controlled properly, can affect the final product. A summary of previous work done is also given.

The third chapter provides the current operating conditions of the elution and electrowinning circuits. It gives the lists of samples points, the analysis done from Anglogold Laboratory and Rand Refineries. The results of the test work while varying different parameters are also summarized.

The fourth chapter provides the observations and results of the experimental run at plant scale followed by the fifth chapter where discussions regarding the results are done. Chapter six will try to model the cathodic reactions and evaluate the single pass efficiency and the deposition rate during the electrowinning. Chapter seven will summarized the best operating conditions based on the results of previous chapters.

A conclusion section will sum up the findings that will allow the plant to operate at optimum conditions in order to improve the fineness of gold.

The appendix will summarized the thermodynamics of electrowinning, the detailed development of models as well as the constants used for the models, data for single pass analysis and deposition rate, actual plant values regarding the fineness and the analysis of different elements during the test work.

CHAPTER 2 LITERATURE REVIEW

2.1 The chemistry and factors affecting elution

Activated carbon is used to adsorb gold that is leached by cyanide solution. The gold is then stripped from this loaded carbon by means of elution to form a concentrated eluate which is then processed for gold recovery by electrowinning. Essentially elution is the reverse of the adsorption process. Some of the base metals that are contained in the ores are also leached with cyanide and loaded on the carbon in the CIP process.

Some of the factors that influence the elution are: temperature, flow rate, gold in the eluant, free NaOH. The washing of loaded carbon with a diluted acid prior to the elution and the decomposition of cyanide during elution are known to affect the rate of elution under certain condition. The elution is a slow process that requires from 8 to 96 hours for completion at elevated temperature. This is primarily due to slow down diffusion of aurocyanide ion within the micropores of the relatively large particles of activated carbon.

The adsorption-desorption equilibria of gold cyanide on carbon have been described by linear isotherms (Adams 1986).

The study work of Adams (1990) showed that the adsorption process is thermodynamically reversible. Therefore the chemical and physical aspects that boost elution will inhibit adsorption and vice versa.

To understand the mechanism of elution, it is pertinent to understand the favorable conditions for adsorption and then the reasons why conditions for elution are targeted will become more obvious.

The exact mechanism of gold adsorption is a highly debatable issue. However, it is generally accepted that the adsorption of (metal) ions from the leach solution by the carbon does not involve any slow reactions. The slow steps are associated with mass transport in the solution and solid phases. It is speculated that the rate of elution will be affected by the same processes (Van Deventer et al, 1993).

Gold adsorption occurs as a result of the formation of the metal cyanoaurate anion as given by Adams(1989):

$$M^{n+}_{(aq)} + nAu\ (CN)^-_{(aq)} = M^{(n+)}\ [Au(CN)^-_2]_{n(ads)}$$

$$M^{n+} = K^+, Na^+, Ca^{2+}$$

The degree of gold adsorption on carbon is strongly dependant on the nature and concentration of the alkaline metal cation present in the adsorption medium. Monovalent alkaline metal gold complexes

are less strongly adsorbed than divalent alkali metal gold complexes and thus logically the monovalent complex would be easier to elute from carbon. Thus, the preferred species for the aurocyanide complex before elution takes place would be Na^+ or K^+ forms (Van der Merwe et al, 1991).

The presence of calcium carbonate has only a passivating effect on the rate of adsorption and does not effect the equilibrium capacity of the carbon to adsorb gold, thus suggesting that this passivation effect is purely physical (Van Deventer et al, 1993).

Adsorption is strongly dependant on the pH value of the adsorption medium, the amount of gold adsorbed in the pH range 4 to 7 being almost twice the amount that is adsorbed in the pH range 8 to 12. It should be noted that carbon's selectivity for gold appears to increases with increase in pH and free cyanide concentration. This is probably because at high pH (>10) most other metal cations have precipitated as metal hydroxides.

Creating the opposite physical conditions needed for adsorption is almost the ideal condition for eluting the gold from the carbon. Van Deventer et al (1993) summarize the most important parameters that influence the rate of elution, in order of importance they are as follows: temperature, the concentration of cyanide and caustic and the ionic strength of the eluant or strip solution, water quality and acid treatment. *Steyn (2003)* however recognized there is a plateau on the relationship between the temperature and elution efficiency, and he provided the curve as given below

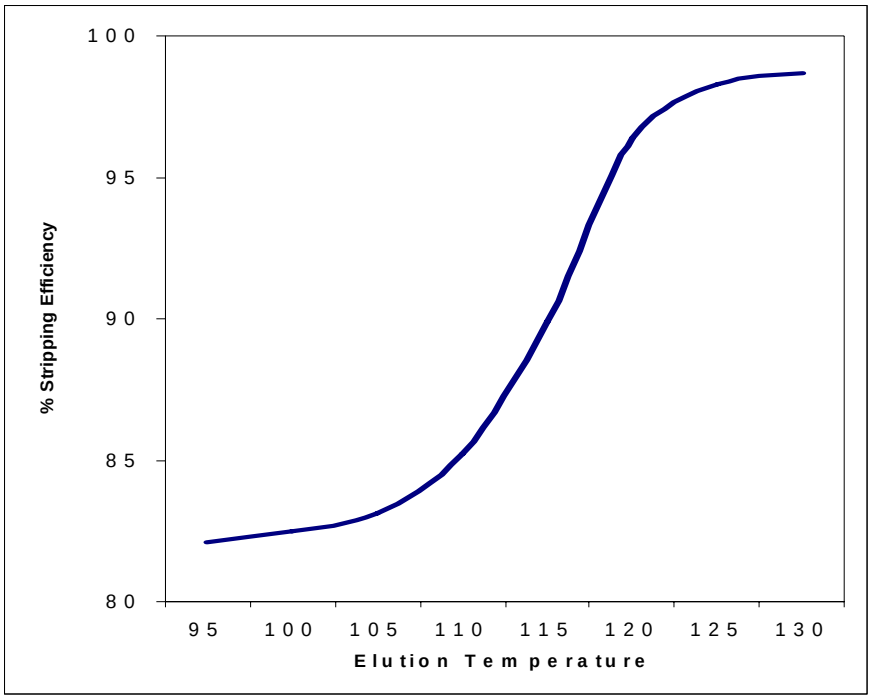


Figure 4 Relation between temperature and elution efficiency

While temperature plays perhaps the most significant role in gold elution, the parameters affecting this are interrelated to some extent, thus making their evaluation and definition somewhat complex.

The adsorption of gold onto activated carbon is an exothermic reaction and an increase in temperature will shift the equilibrium in favor of desorption. High temperature necessitates also the presence of cyanide to prevent the formation of AuCN, which is difficult to desorb (Stanley, 1987).

If calcium dicyanoaurate is present, it is converted to less strongly adsorbed sodium aurocyanate due to the high concentration of sodium in the eluant.

$$Ca\,[Au\,(CN)_2]_2 + 2\,Na^+ = Ca^{2+} + 2\,NaAu\,(CN)_2$$

At reduced temperature and low concentrations of gold (to achieve low levels of eluted carbon grades) and calcium ions in the fresh strip solution, the ion further dissociates to:

$$NaAu\,(CN)_2 = Na^+ + Au(CN)^-$$

In his thesis, Banini (1993) confirms that gold is adsorbed as $Au\,(CN)^-_2$ ion pair. He continues by stating that for elution to be favored, it demands that the solution have a low concentration of spectator ions like K^+, Na^+ and Ca^{2+}, hence low ionic strength.

The deleterious effect of free cyanide on the adsorption of the aurocyanide complex is believed to be related to competitive non-specific adsorption and this effect becomes more pronounced if the temperatures are increased. Hence, a high free cyanide is often used to drive the desorption of gold from the carbon reaction. It is also thought that cyanide is necessary for faster elution rates and that it promotes more “complete” elution of gold from carbon (Van Deventer et al, 1993).

Increasing the concentration of cyanide or caustic to too high level will start to have deleterious effects on the elution rate. The high ionic strength of the eluant will start to counteract the positive benefits of these reagents, as well as lead to wastage of the reagents and production inefficiencies.

It is reported by Adams (1989) that cold acid washing results in the limited formation of an AuCN type species, the reactions being considerably more marked when hot washing is employed. From gold elution point of view, the AuCN formed is very difficult to elute. Van Deventer et al (1993) have shown that after the acid washing steps, only 50% of the loaded gold on the carbon can be desorbed by regional water. To convert the AuCN formed into a state that is amenable to elution, presoaking is employed. Presoaking converts the AuCN to $Au\,(CN)^-_2$ which is easily eluted with good regional water.

Apart from the removal of calcium, zinc and nickel which influence gold elution, acid washing has an effect on the adsorption process. Without acid washing poor adsorption may be encountered.

This is due to the passivation of the carbon surface with calcium carbonate. Acid washing destroys the calcium carbonate hence liberating the carbon for adsorption. Because of the difficulties of eluting AuCN formed after the acid washing stage, some newly built plants employ acid washing after the elution.

2.2 Kinetics of gold elution

There is no clear picture on the kinetics of gold elution. It is accepted that if the thermodynamic driving forces for the elution exist, the elution of gold cyanide from activated carbon can take place in a number of sequential and/or parallel transport and reactions steps.

Vegter et al (1992) summarized the rate steps as:

1. Mass transport of gold cyanide and cations across the solution films surrounding the carbon particles.
2. Transport of the dissolved species in the solution-filled-pores by pore diffusion.
3. The adsorption/desorption reactions and transport of the adsorbed cation gold cyanide ion pair along the pore walls by surface diffusion

As yet the rate-limiting step(s) for elution have not been isolated as concluded by Vegter (1992).

Experimental investigations have shown that the rate of elution is sensitive to changes in the temperature and solution composition.

Vegter (1992) listed the work of many authors who investigated the effect of solution composition on the elution rate.

Van Deventer (1986) discovered a much faster rate of elution of gold cyanide for carbon that was pre-loaded for 15h and eluted in distilled water at ambient temperature than could satisfactory explained by a mass transfer rate- controlled adsorption model.

Adams and Nicol (1986) have shown the positive influence of increasing cyanide concentration and negative effect of increasing ionic strength on the rate of elution. They have also investigated the influence of flow rate on the elution as well the electrowinning process.

However, Espiel et al(1988) demonstrated that the omission of cyanide from the aqueous caustic acetone solution had little effect on the rate and extent of elution. The rate of elution was strongly dependent on the acetone to aqueous solution ratio and temperature, but virtually independent of the caustic concentration in the 1-20 mg/l NaOH range.

2.3 Electrochemical reactions of gold electrowinning

The following electrochemical reactions are of relevance during the gold electrowinning process as described by Barbosa et al (2001):

$Au(CN)^-_2 + e^- = Au + 2CN^-$ (1)

$E = -0.6 + 0.059*\log [Au (CN)_2] – 0.118 \log [CN^-]$

$O_2 + 2H_2O + 4 e^- = 4 OH^-$ (2)

$2 H_2O + 2e^- = H_2 + 2OH^-$ (3)

$E = -0.4 – 0.059 \log [OH^-]$

$2 H_2O = 4 H^+ + O_2 + 4 e^-$ (4)

$E = -0.83 – 0.059 \log [OH^-]$

$2OH^- + CN^- = CNO^- + H_2O + 2 e^-$ (5)

$E = -0.97-0.0295\log [CN^-] + 0.0295 \log [CNO^-]- 0.059 \log [OH^-]$

Where E represents the electrode potential required for the reaction to occur and the squares brackets, the species activities in solution.

The gold, which is present in the solution in the form of aurodicyanide [$Au (CN)_2^-$], is reduced to metallic gold, according to the equation (1).

Reaction (2), representing oxygen reduction in alkaline solutions, is one of the main cathodic reactions competing with gold deposition and consumes a significant fraction of the available current flowing to the cathode, as the electrolyte is likely to be saturated with oxygen due to the oxygen evolution occurring at the anode.

Reaction (3) represents the hydrogen evolution that commences at a potential of -1.2 V (SCE). The evolution of hydrogen is under kinetic control at all potentials within the bed and therefore consumes a high proportion of the cathodic current.

The major anodic reaction is the oxidation of water to oxygen as described by reaction (4), accompanied by the kinetically slower oxidation of cyanide to cyanate as given by reaction (5)

Cyanide can also be oxidized in bulk solution by dissolved oxygen.

Other metals like silver, copper, nickel and iron will also from complexes with cyanide.

The relevance of some of these metals will be studied in this project.

Steyn (2003) provides the equilibrium potentials for the reduction of various metals cyanide ions as given in Table 1

Reactions		N	$E_{aq,}$ (V) (SHE)
$Pb(CN)_4^{2-}$ →	$Pb + 2e^-$	2	-0.38
$Ag(CN)_2^-$ →	$Ag + e^-$	1	-0.45
$Au(CN)_2^-$ →	$Au + e^-$	1	-0.63
$Cu(CN)_3^{2-}$ →	$Cu + e^-$	1	-0.75
$Fe(CN)_6^{4-}$ →	$Fe + 2e^-$	2	-0.99
$Ni(CN)_4^{2-}$ →	$Ni + 2e^-$	2	-1.07

Table 1: Equilibrium potentials for metal cyanides

From Table 1, it is evident that lead and silver will thermodynamically plate out preferentially to gold since the reduction potentials of these metal-cyanide complexes are more positive than that of the reduction of the aurodicyanide ion.

Note that thermodynamics only gives an indication of the species that will be most stable but, it does not state anything about the kinetics or the rate of the reactions. It may therefore be possible that although a specie can be thermodynamically stable under certain conditions, it may be kinetically unfavorable to achieve this stability due to very slow reaction rates which will lead to impractical retentions times. Therefore a study of the kinetic appears important.

2.4 The kinetics of gold electrowinning

The rate determining steps of the electrowinning reaction is characterized the rate at which gold is deposited onto the cathode surface. The reaction is either kinetically controlled or mass transport controlled.

The kinetically controlled reaction implies that the rate of reaction of reduction of aurocyanide to solid gold at the cathode surface is slower than the rate of the diffusion of aurodicyanide ions across the boundary layer to the cathode surface.

The mass transport controlled reaction is where the diffusion of aurodicyanide ions across the boundary layer to the cathode surface is slower than the reduction reaction of gold on the cathode surface. In the latter case a concentration gradient of gold in solution exists across the boundary layer. (Steyn, 2003)

These principles are illustrated in Figure 5 below.

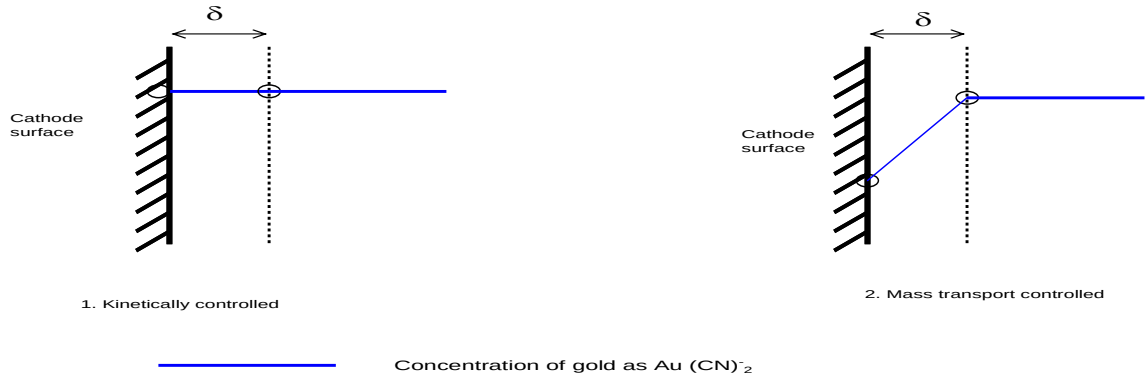


Figure 5: Illustration of the effect of 1. Kinetically and 2. Mass transport controlled processes on the concentration of gold in solution across boundary layer (δ)

From Figure 5, it is evident that the highest practical deposition rate occurs when the diffusion of aurodicyanide ions to the cathode surface is the rate limiting step. It is therefore important that as soon as Au $(CN)^-_2$ ions enters the boundary layer and reaches the cathodes, it must be able to separate into Au^+ and CN^- and then allow the gold in solution to be reduced to solid gold without being prevented from doing so by a slow chemical reaction on the cathode surface (Steyn, 2003).

Deposition of gold from alkaline cyanide electrolyte does not occur until a potential of -1.0 V (SCE) is reached. The exact potential depends on the solution composition and temperature. Between potential of -1.0 V and -1.3 V (SCE) the rate of deposition is chemically controlled. At these potentials, an increase in the electrode potential will result in the increase in the rate of electrowinning. At potentials more cathodic than -1.3 V (SCE), the rate of deposition is mass transport controlled. The evolution of hydrogen commences at -1.2 V. It is clear that to maximize the gold deposition rate the concurrent evolution of hydrogen occurs. Thus, the current efficiency will decrease with the increase in cathodic current, while the extraction efficiency will increase to a maximum and will then be virtually unaffected by further increase in current. The optimum operating current is therefore that value at which the deposition of gold changes from chemical to mass transport control.

Further aspects of its thermodynamics of gold electrowinning are given in the Appendix.

2.5 Previous work on the effects of base metals

Not as much has been written on the impact of base metals on elution and electrowinning.

Fisher and Labrooy (1997) have assessed the impact of nickel in leach, electrowinning and elution. They discuss the competitive adsorption of gold and nickel cyanides onto activated carbon and investigate the changes in solution parameters that may improve gold adsorption and/ or inhibit nickel adsorption. In addition, they discuss the selective removal of nickel from carbon by acid washing, prior to gold elution by means of different physical and chemical conditions. They also recommend a change in the cyanide content in the eluate to keep the nickel out of solution during electrowinning.

CHAPTER 3 EXPERIMENTAL

3.1. Current operating conditions and equipment sizes of the elution

The Zadra elution as used in the Tau Lekoa stream operates with a heated solution of 2-2.5% NaOH. The solution is preheated with Alpha Laval plate exchanger. Figure 6 shows the process lay-out.

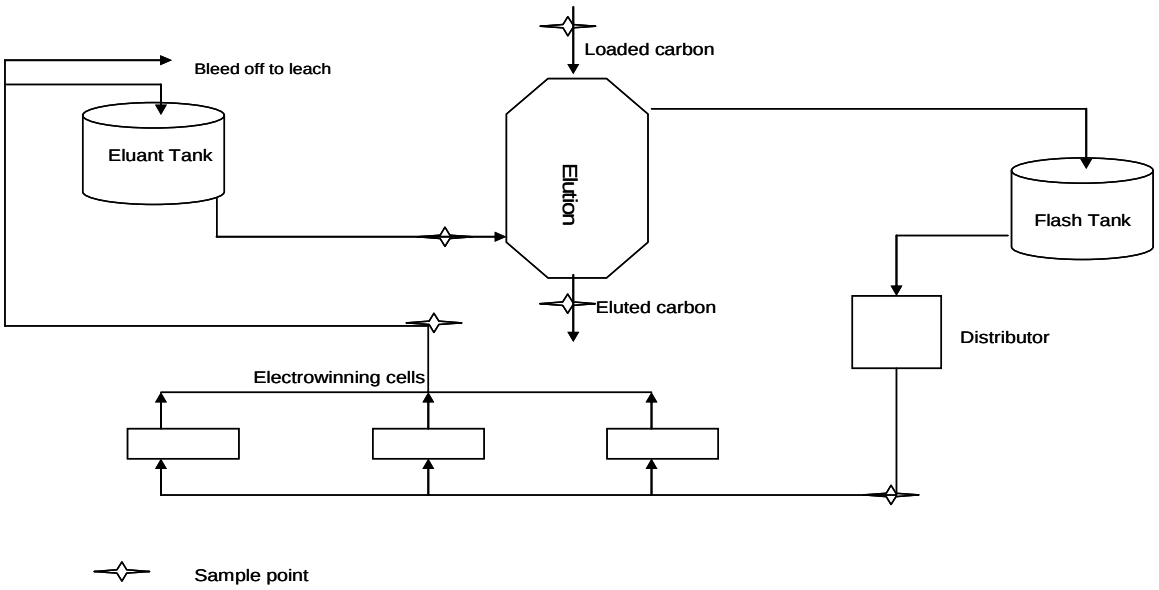


Figure 6 Elution and electrowinning circuit with sample points

The eluate reports to a flash tank and is distributed through the electrowinning cells, in parallel, from where spent electrolyte is returned to the eluant tank. A bleed off of spend electrolyte is done to avoid a build up of base metal and salt concentrations.

The elution process is affected by the spent electrolyte gold concentration and circuits are normally run at lower flow rate to gain higher single pass efficiencies.

The size of the column is 135 m^3 with 10 beds. The gold carbon load is between 1300-2200 g/t and the eluted carbon is between 200-250 g/t with an elution efficiency of 84-90%. The average concentrations of the loaded impurities on the carbons are Ag ~200-800g/t, Ni ~6500g/t, Fe ~360 g/t, Cu ~500 g/t, Zn ~160 g/t.

The elution takes place at a temperature of 135 ^{o}C. The continuous carbon regeneration with 5% HCl washing in series with a rotary kiln takes place in the circuit. The production is 8-9 strips per week.

3.2 ***Current operating conditions and equipment sizes of the electrowinning***

The electrowinning cells are continuously supplied with electrolyte, except when there is a strip. The flow sheet is given in Figure 6.

The circuit possesses 6 electrowinning cells in series and each cell contains 8 cathodes and 9 anodes. They are contained within a rubber-lined stainless steel box. The applied potential difference is 10 V and the applied current varies between 600-620 A. The electrowinning circuit operates for 48 hour and the temperature of the eluate entering the circuit is controlled at 80-85 ^{o}C. The average electrowinning production is between 0.6 to 1 kg per cathode.

3.3. Sample collection and analysis

Samples were collected in the plant at the elution columns at specific points as indicated by star(*) and the final bullion is be sampled at Rand Refineries. The initial test work was run from May 2006 up to August 2006. The last test work was run in November 2006 for the electrowinning section.

The samples for loaded carbon, eluted carbon, eluate and eluate solutions were collected during the experiments. The analyses of base metals, silver and gold were done in the solution samples (eluate and eluant) and the same analyses were done for the solids samples (loaded and eluted carbons).

The above analyses were done whilst varying the elution flow, temperature and caustic soda strength.

Operational data like the inlet and outlet elution temperatures and pH as well the free caustic strength were recorded. The elution time was kept constant at 18 hour during the experiment.

All samples were analyzed in the Vaal River Laboratory, Anglogold. Gold bullion sampling and analysis was done at Rand Refineries, Johannesburg.

3.3 Parameters changed

Three elution flows rate were tested at 25, 30 and 35 m^3/ h , the elution temperatures as well the strength of the free NaOH were also changed during the tests. The operating conditions as described above were recorded and the elution efficiency of different elements were calculated whilst the fineness of gold was evaluated. The results of the experiment are given in the next chapter.

CHAPTER 4 RESULTS

From the experiments run on the plant scale, four major findings could be highlighted:

- Excellent finenesses are achieved in the temperature range of 120-125 ºC
- Nickel content in the loaded and eluted carbon are high
- Zinc and Cobalt did not elute during the elution
- Change in cyanide strength did not improve the fineness of gold

The Appendix 7 summarizes the data collected in the plant as well as the fineness of gold in the bullion

Three different flows were tested during the elution and elution efficiencies were calculated for gold, silver and the impurities. Table 2 summarizes those results are given below.

- Copper had a high elution rate
- Poor finenesses were achieved when the elution of Ni and Cu took place at 25 m^3/ h
- Silver elution efficiency was related to the flow
- Cobalt and Zinc do not elute
- The flow of 35 m^3/ h showed low elution efficiency of gold but the flow 25 m^3/ h showed poor fineness of gold and better elution efficiency
- Best flow was 30 m^3/ h with regard to elution efficiency and fineness of gold

Elution flow (m^3/h)	**25**	**30**	**35**
Average Au elution efficiency (%)	85	84	70
Average Ag elution efficiency (%)	81	78	68
Average Ni elution efficiency (%)	27	11	12
Average Cu elution efficiency (%)	90	90	82
Average Zn elution efficiency (%)	0	1	0
Average Co elution efficiency (%)	0	0	0
Fineness	73	80	76

Table 2 Elution efficiencies at different flow rates

As the temperature reaches a plateau around 120-125 ºC regarding the elution efficiency as given on page 16, it was decided to run the experiment in this range of temperature and utilize the flow of 30 m^3/ h and vary the free NaOH concentration.

The results achieved are summarized in Table 3. While comparing these results with Table 2, the following observations were made:

- Improvement of fineness of gold by 3%
- Improvement of elution efficiency of gold by 1.5%

- Improvement of elution efficiency of silver by 3%
- Decrease in elution efficiency of nickel and copper

Elution flow (m^3/h)	**30**
Temperature (ºC)	**120-125**
Average Au elution efficiency (%)	87
Average Ag elution efficiency (%)	82
Average Ni elution efficiency (%)	5
Average Cu elution efficiency (%)	72
Fineness	84

Table 3 Elution efficiency with reduced NaOH

The concentration of free caustic could not be reduced below 1.5 % as the current did become unstable and fluctuated severely below 600 A. The resulting deposition of gold was poor.

Another test was run at a flow rate of 30 m^3/ h and temperature range of 120-125 ºC whilst the pH was varying. The results are summarized in Table 4 and the following observations can be made:

- Low fineness are achieved at high pH
- Elution efficiency for copper and nickel increased

pH	**11..12**	**12…13**	**>13**
Average Au elution efficiency (%)	85	84	70
Average Ag elution efficiency (%)	81	78	68
Average Ni elution efficiency (%)	8	9	23
Average Cu elution efficiency (%)	80	82	90
Fineness	80	84	81

Table 4 Elution efficiency whilst varying the pH

The last test was run by varying the cyanide strength whilst keeping the pH, the temperature and flow rate constant at the best operating conditions. The results are summarized in Table 5. It was observed that the fineness of gold did not improved when comparing the results with Table 3.

Free cyanide (%)	**0.05**	**0.70**	**0.10**
Average Au elution efficiency (%)	85	84	85
Average Ag elution efficiency (%)	82	83	81
Average Ni elution efficiency (%)	11	9	10
Average Cu elution efficiency (%)	80	79	77
Fineness	84	83	84

Table 5 Elution efficiency whilst varying the free cyanide

The discussions regarding the observations and results are given in the next chapter.

CHAPTER 5 DISCUSSION ON THE ELUTION SECTION

5.1. Influence of temperature

Temperature is probably the variable that has the greatest effect on the elution rate. As was previously stated, the adsorption and elution rates are both adversely affected by the variation of temperature.

The test run showed that the best elution was achieved when the temperature was between 120 - 125^{o}C. This finding is confirmed by the graph supplied by Steyn (2003) where he showed the effect of temperature on stripping efficiency. This result confirmed the fact that the elution is an endothermic process i.e. an increase in temperature will benefit the process. The increase of temperature has to be limited as it can favor the formation AuCN. As it is known, AuCN can slow down the elution. This is seen when the temperature reaches 130^{o}C when no increase in the efficiency will be expected, as showed by Figure 3. It can also be said that an increase in temperature above 125^{o}C is a waste of energy.

5.2 Influence of flow rate

Adams and Nicol (1986) stated that the overall rate of elution is influenced by the flow rate and they have developed a model that links the elution efficiency to the flow rate.

However, Van Deventer et al (1993) reported that elution efficiency is independent of the flow rate in the range 1 to 5 bed volumes (BV) per hour if the length to diameter ratio is 10 or more.

At Kopanang, this parameter is above 10, which means that the flow rate will have an impact on the elution efficiency. From the test work, it has been confirmed that the flow rate has an impact on the efficiency of elution and the quality of the final product.

High flow rate (35m^3/h) showed low elution efficiency although the fineness was better compared to low flow rate (25m^3/h). It has also been observed that low fineness was achieved when the flow was reduced to 25 m^3/h as the elution of nickel and copper was very high. The effect of flow rate is probably related to the fact that channeling of the strip solution takes place through the carbon bed. Obviously, down flow column, as applied in the plant is more susceptible to channeling of the elution solutions and hence the effect of flows rate appear to be more critical.

The flow rate of 30 m^3/h seems to give reasonable results in terms of elution efficiencies and gold fineness as summarized in Table 2.

The low flow rate (25 m^3/h) provides more residence time is achieved in the column, therefore more elution of gold and base metals, especially copper and nickel will take place. Although the elution efficiency is improved, the increase in base metal affects the fineness of the final gold.

The high flow rate (35 m^3/h) during elution can assist with more elutions per cycle with an adverse effect on the stripping efficiency. A high flow rate limits the elution of base metals but will provide low elution efficiency as the residence time in the column is reduced.

The high flow rate appears to short circuit the columns and therefore the elution appears to be not completed.

The observation that comes from experience is that the elution is a more diffusion controlled mechanism. This was confirmed by Deventer et al (1993). However, high flow rate had a negative impact on the overall efficiency of the electrowinning process as predicted by Adams and Nicol (1986)

5.3 Influence of pH

The reduction of pH seems to improve the elution of gold. This was probably enhanced by the fact that the test work was run in the temperature range of 120 - 125^oC. It appears that the base metals did have a low (poor) elution rate at lower pH. This is observed in Table 3. It appears that the low caustic strength had the effect of keeping the base metals in the carbon. Although the gold fineness did improve, it is expected that the downstream process (electrowinning) is affected as it requires high pH to favor gold deposition as given by the Pourbaix diagram in Figure 4.

5.4 *Influence of cyanide in elution*

Another test was run in late August 2006, the main change being the addition of cyanide in the elution circuit. This test was run by keeping the optimum condition as found in the previous test work i.e. the temperature range of 120-125 ° C in the elution with a pH close to 11-12 and the flow rate of 30 m^3/ h. It was observed that there is no improvement in the fineness of the final gold by comparing the fineness. This is in contradiction to the recommendation given by Fisher and Labrooy (1997). The result seems to be disappointing.

CHAPTER 6 MODELLING THE CATHODIC REACTIONS AND EXTRACTION RATE

6.1 Cathodic reactions

The feed solution contains mainly gold and silver in solution. This is contaminated by impurities such nickel, copper and iron that have been eluted. Depending on the operating conditions and their concentration, these impurities usually co-deposit with the gold and silver in the electrowinning stage. Therefore it is important to formulate a model containing a set of reactions which includes the deposition of gold and silver while minimizing the co-deposition of base metals. This model will derive from the Nernst Equations as basis.

The following reactions, as provided in Chapter 2, are expected to takes place on the cathode:

$Au(CN)^-_2 + e^- = Au + 2CN^-$ (1)

$2\ H_2O + 2e^- = H_2 + 2OH^-$ (2)

$O_2 + 2H_2O + 4\ e^- = 4\ OH^-$ (3)

$M^{n+} + ne^- = M\ (s)$ M^{n+} : Ni, Cu, Fe (4)

The reduction reaction of metal is given by the relationship: $E = E^{\circ} + \frac{RT}{nF}\mathrm{Ln}[\text{Complex } M^{n+}]$

where *R, T, n , F and C* are the gas constant (8.314 J mol^{-1} K^{-1}), temperature (in K), the valance of the metal ion in solution (n), Faraday constant (96485 C) respectively and C is the concentration of the particle involved. The potential $\Delta E°$ of the cyanide metals involved in the cathodic reactions for the production of gold and silver are given in Table No 6.

Reactions	N	$E_{aq,}$ (V) (SHE)
$Ag(CN)_2^- \longrightarrow Ag + e^-$	1	-0.45
$Au(CN)_2^- \longrightarrow Au + e^-$	1	-0.63
$Cu(CN)_3^{2-} \longrightarrow Cu + e^-$	1	-0.75
$Fe(CN)_6^{4-} \longrightarrow Fe + 2e^-$	2	-0.99
$Ni(CN)_4^{2-}$ $Ni + 2e^-$	2	-1.07

Table 6: Equilibriums potential for metals cyanide

Hydrogen evolution starts at a potential of E= 0 and the metal deposition will start at a potential E= - 0.45 V for silver, E = - 0.63V for gold, E = -0.75 V for copper, E = -0.99 V for iron and E = -1.07 V for nickel

The Nersnt equation for each metal involved in the cathodic reactions is:

$$E_{Ag} = E^{0}_{Ag} + \frac{RT}{F}\text{Ln}\,[Ag(CN)_2^-] \quad (1)$$

$$E_{Au} = E^{0}_{Au} + \frac{RT}{F}\text{Ln}\,[Au(CN)_2^-] \quad (2)$$

$$E_{Cu} = E^{0}_{Cu} + \frac{RT}{F}\text{Ln}\,[Cu(CN)_3^{2-}] \quad (3)$$

$$E_{Fe} = E^{0}_{Fe} + \frac{RT}{2F}\text{Ln}\,[Fe(CN)_6^{4-}] \quad (4)$$

$$E_{Ni} = E^{0}_{Ni} + \frac{RT}{2F}\text{Ln}\,[Ni(CN)_4^{2-}] \quad (5)$$

By replacing the value of $E°$ of each metal in the equations given above and the multiplying out different constants with F = 96500, R= 8.314 J mol^{-1} K^{-1} , the potentials of the cyanide metals for the deposition of the metals will be known. The model for the deposition of gold preferentially to nickel will be given by the equation as $E_{Au} > E_{Ni}$:

$$\frac{10233}{T} > (\text{Ln}\,[Ni(CN)_4^{2-}] - 2\,\text{Ln}\,[Au(CN)_2^-]) \quad (6)$$

This relation is limited to the temperature above 75ºC, as any temperature below that will affect the kinetics of gold deposition.

The derivation model is given in the appendix.

6.2 Single pass analysis and extraction rate

Three different tests were conducted over a period of 10 days to evaluate the deposition and extraction rate of gold, silver, copper and nickel. The main purpose of the test was to determine the relative competition during the metal deposition period. Samples of electrolyte were collected hourly and they were analyzed for the above metals.

Figures 7 and 8 show that the single pass extraction rates of gold and silver increase when their concentrations increased. The figures show also that single pass extraction rate of Nickel increase at higher nickel concentration.

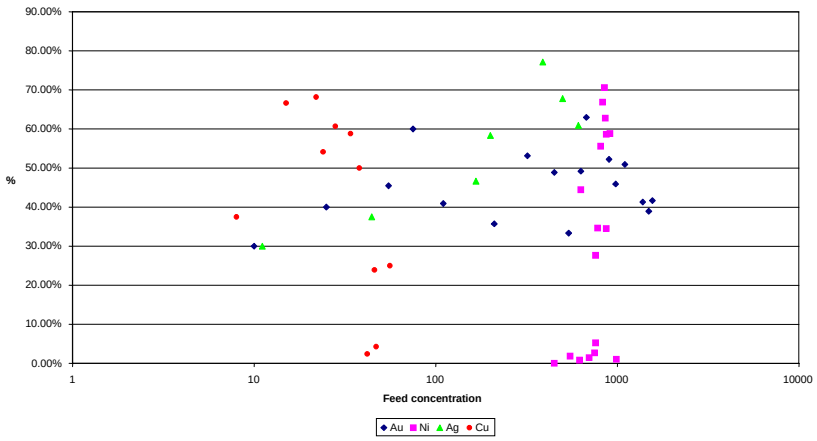


Figure 7 Single pass efficiency 14/11/2006

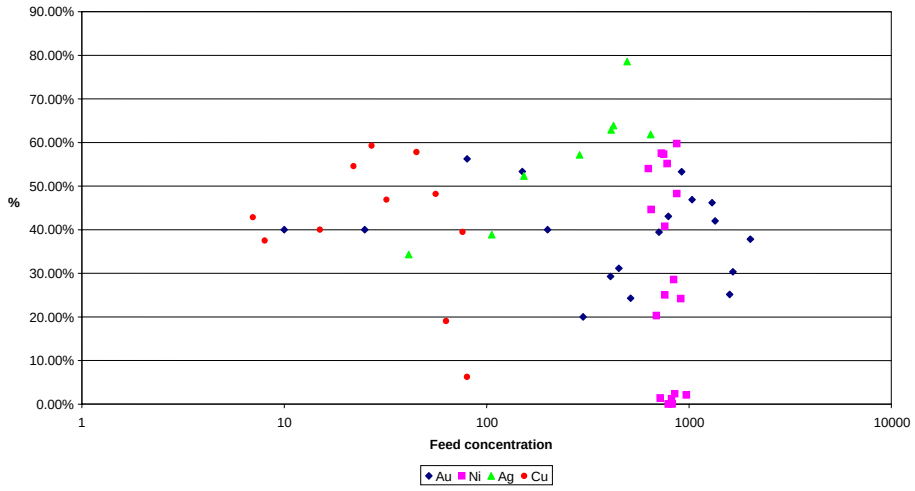


Figure 8 Single pass efficiency 16/11/2006

Figures 9 and 10 also show their also the extraction rates. These depend on the reduction potential, where silver has the higher deposition rate than any other metals tracked. Whenever silver is depleted from solution, gold and copper start depositing in preference to nickel. The nickel deposition rate starts increasing when silver and copper are depleted in the solution, therefore gold will start competing with nickel for deposition. This is the confirmation of the model described by the relation (6) that proves that the deposition of metals depends on their concentration in the solution. This indicates that the way to solve contamination of the final product is to reduce the electrowinning time as the nickel deposition rate increases whenever the gold deposition rate decreases.

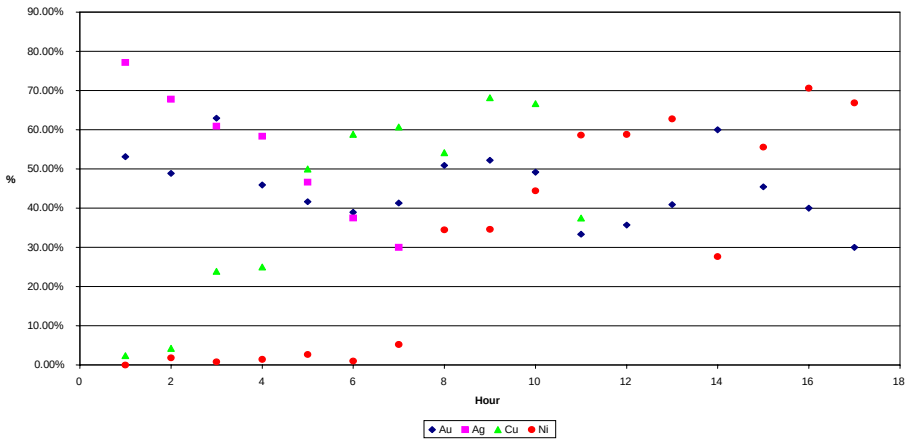


Figure 9 Single pass efficiency versus time 14/11/2006

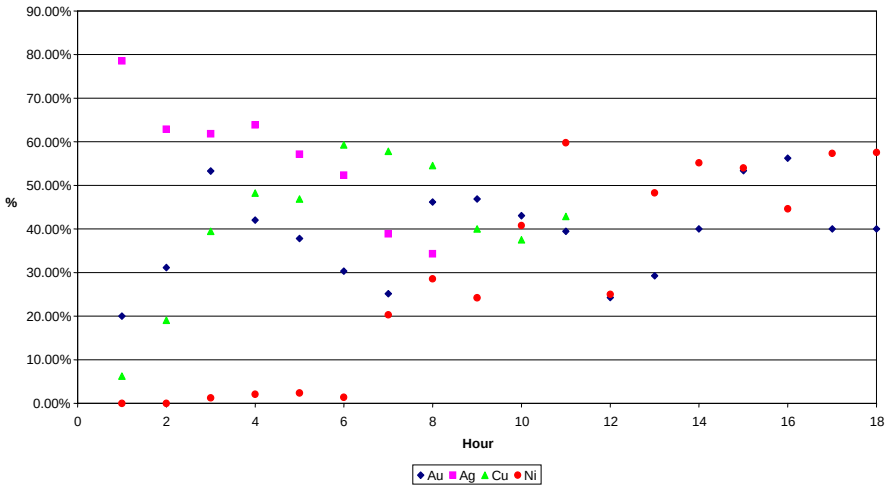


Figure 10 Single pass efficiency versus time 16/11/2006

A special test was run with the elution and electrowinning time reduced from 18hours per cycle to 15 hours per cycle to address the preferential deposition of nickel after the depletion of gold. This has resulted in an increase of gold fineness from 83.8 % to 85.2%. This reduction of electrowinning time was adopted on the plant. The single pass efficiency versus time is plotted in Figure 10.

This Figure shows clearly that the nickel deposition rate was much faster after 8 hours of electrowinning. This is because of the depletion of silver and copper and the decrease in the concentration of gold. This is the confirmation of the model given early on in Chapter 6.1.

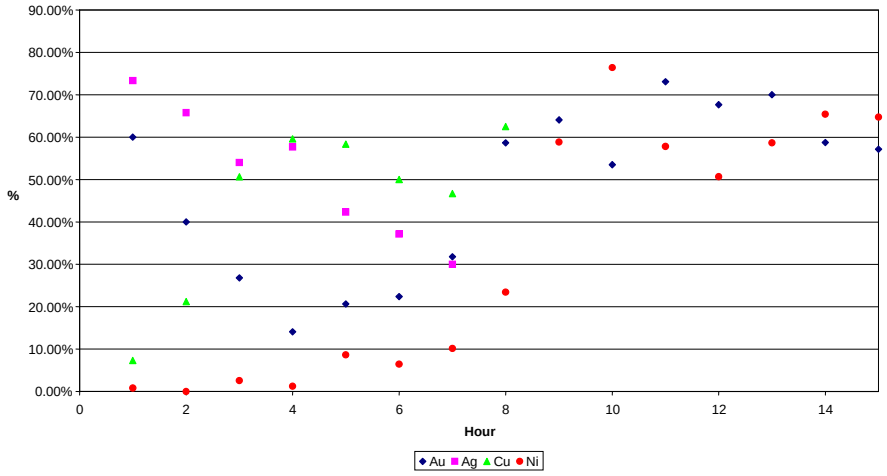


Figure 11 Single pass efficiency with short time 27/11/2006

CHAPTER 7 CHANGES TO THE OPERATING CONDITIONS

7.1 Elution

The experiments run, at plant level, did show that the fineness of gold depend on three parameters. These parameters are the temperature, the flow rate of the elution, the pH (or the free caustic soda strength). Although literature advises that an increase in cyanide concentration in the eluate improve the fineness, the current test work did not show any substantial improvement in the quality of the final gold when this was tried.

The fineness of gold during the test work increased from 80% to 84 % by operating the plant in the range of optimum conditions. These optimum operation conditions favor the elution of gold and at the same time create the conditions that minimize the elution of base metals.

These conditions are summarized in Table 7 below

Temperature (ºC)	120-125
Elution flow (m^3/h)	30
pH	12…13
Electrowinning time (Hour)	15

Table 7 Optimum operating conditions

It is also important to note that the operating condition as recommended by Fisher and Labrooy (1997) did not show the expected results during the plant test work. This might due to the fact the electrowinning process was not run at the recommended pH. This could be interesting to explore in the future. The change that is required to run this successfully would be to add cyanide and caustic after the elution. This will allow to increase the cyanide strength and run the electrowinning at the recommended pH of 13.

7.2 Electrowinning

The extraction rate during the electrowinning was also monitored and it was found that the deposition rate of nickel started taking place after 9-10 hours. This was justified as the concentration of copper and silver were depleted in the electrolyte and the concentration of gold was reduced, therefore it was suggested to reduce the electrowinning cycle time from 18hours to 15 hours, this did show an improvement of the fineness by 1 %, bringing the total improvement in the fineness from 80% to 85%.

The benefice of the higher fineness is the reduction of the refining costs as it is reduced due to fewer impurities that have to be reduced.

CONCLUSION

This project focused on the elution and electrowinning sections as the base metals contained in the reefs were leached, loaded and eluted during the leach, the CIP and elution stages. The same base metals end up in the final gold during the electrowinning process.

Prior to starting the experimental phase, the main focus was to understand the kinetics of the gold elution and electrowinning processes.

Four parameters were critically evaluated in the elution process namely, the flow rate, the temperature and the pH (or free caustic soda concentration) and the cyanide concentration. Three of the four parameters had an impact on the elution process but the most significant ones were the temperature and the pH.

It was found that running the elution at a temperature of 135 º C did not improve the elution as the best average temperature range was found to 120 ºC - 125 ºC. Any increase of temperature favors the formation of AuCN, which is known to slow down the elution efficiency.

The reduction of free caustic from the range of 2-2.5% to 1.5-1.9% also assisted in the improvement of the fineness as the low caustic strength had an effect of keeping the base metal on the carbon, especially nickel.

Therefore two parameters were reduced in a range that would favor the elution of gold only and restrict the elution of the nickel.

The increase of flow rate (35 m^3/h) resulted in the deterioration of elution efficiency of gold and other base metals compared to when flow rate is 30 m^3/h. This is due to the shortage of residence time in the column.

The reduction of flow rate to 25 m^3/h did improve the stripping efficiency but this has resulted in the deterioration of the fineness as more gold and base metals were stripped. The flow rate of 30 m^3/h appears to be the best flow rate for the elution as the elution efficiency and the fineness of gold were excellent compared to the other two flow rates.

However, some authors like Kar (1995) claims the increase in cyanide concentration improve the elution efficiencies, but this was found not to be the case in this study.

From these parameters, a new elution operating strategy was implemented. This resulted in the improvement of the fineness from 80 % to 84 %. It appears clearly that the combination of temperature range and free caustic concentration are the predominant factors that maintain base metals on the carbon and assist in the improvement of the fineness.

On the electrowinning section, a model related to the thermodynamics was formulated. This model showed clearly that the fineness of gold depends on the concentrations of gold and nickel and on temperature.

The single pass efficiency and the extraction rate were tracked in the electrowinning. It was found that during the deposition of gold on the cathode, silver and copper were depleted first and whenever the concentrations of these metals were reduced in the solution, nickel started to deposit therefore affecting the quality of the product. The deposition of nickel was time dependant as after 9-10 hours, its extraction rate increased drastically and the one for gold decreased. It was therefore decided to reduce the electrowinning time from 18 hours to 15 hours. This resulted in the improvement of the fineness from 84 % to 85 %.

The advantage of the increased fineness is the reduction of the refining costs as the final bullion does have lesser impurities. This is due to the relationship between the fineness and the refining costs.

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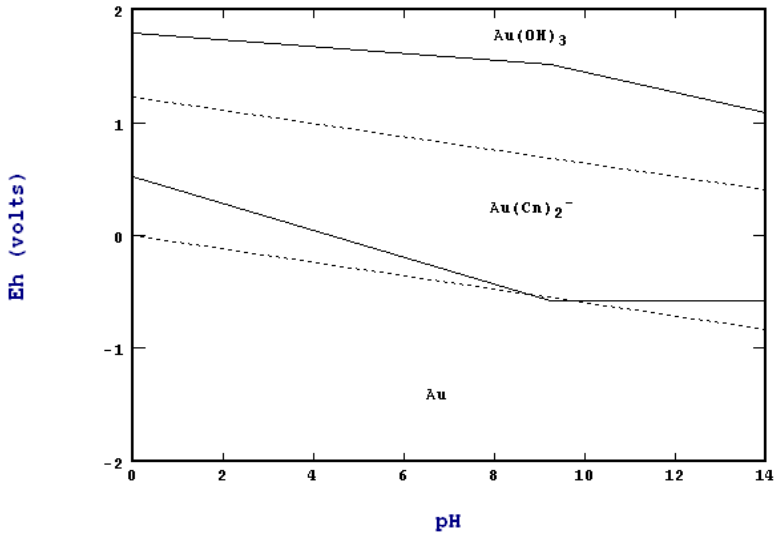
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APPENDIX

1. Thermodynamics of gold electrowinning

It is important, from electrowinning point of view, to know which species will be stable at specific potentials and pH values. Pourbaix introduced the E-pH or Pourbaix diagram on which the dominant species for a system are indicated as a function of the potential, pH and the ion activity. A typical Pourbaix diagram for the Au/CN/H_2O system is shown in Figure a



Pourbaix Diagram Au/CN/ H_2O

The two parallel dotted lines indicate the O_2/ H_2O line (top dotted line) and H_2O/ H_2 line (bottom dotted line). The slope of these line is -0.06 V per pH value implying that the electrode potential for the reduction of water is 0 at a pH 0 of whereas this value changes to -0.78 V at a pH of 13. The water or aqueous stability region exists between these two lines which, from Figure 1, indicates that gold will be in solution as $Au(CN)^-_2$

In general, pH values above 13 are used in some Electrowinning cells to minimize corrosion of the anodes caused by the localized drop in pH due to the reduction of water taking place at the anodes which produces H^+ ions. To plate gold it will be necessary to lower the potential of the cathode to below that indicated by the lines separating the Au and $Au(CN)^-_2$ stability fields.

From Figure 11, it can be seen that when operating at pH values of 13 and conditions as specificied, a potential more negative than -0.5 V (SHE) need to be applied in order to plate gold.

This can be done as follow:

In order to plate gold the reduction of aurodicyanide to solid gold needs to occur as discussed in the half-reaction below: $Au(CN)^-_2 + e^- = Au + 2CN^-$

For electrochemical reaction to take place the resultant electrode potential needs to be positive in order to obtain a negative Gibbs free energy value.

A negative ΔG value indicates the electrochemical reaction can occur

ΔG= -nFE, where E is the overall reaction potential, F is the Faraday constant and n is the number of electron transferred.

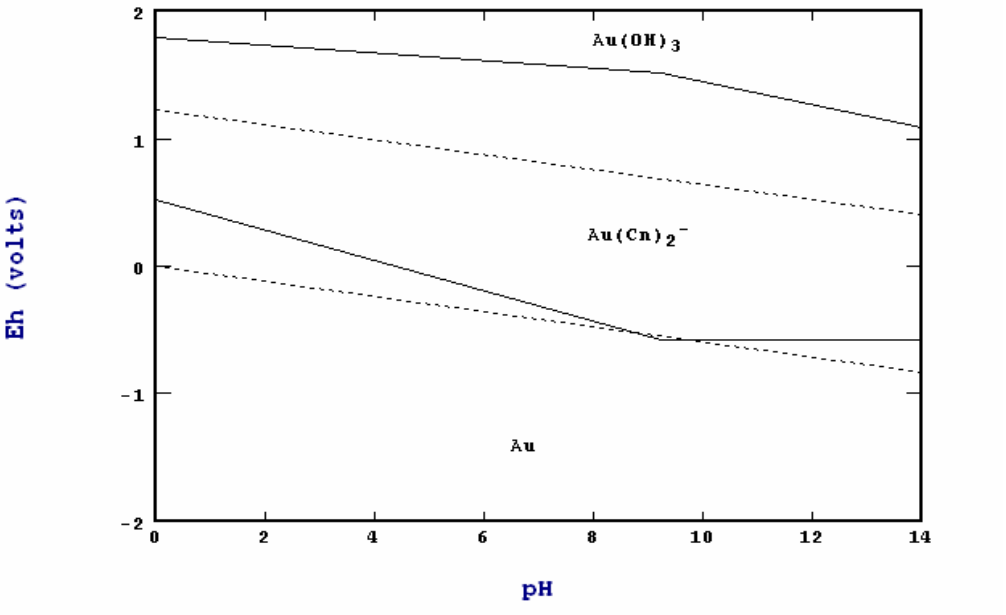
It is therefore necessary to apply a potential more negative than -0.5 V to acquire a positive overall potential as explained below:

$E_{resultant} = E_{reduction} - E_{applied} = -0.5-(0.6) = 0.1$ V

In this case an over potential of 0.1 V was applied.

The size and location of predominance regions is dependant on the concentrations of the different species involved. Consequently, the electrode potential needed for the plating of a metal will depend on the cyanide concentration, the concentration of the metal in the solution and the level to which it must be removed. This can be determined from the Pourbaix diagrams or by using the Nernst equation: $E = E° - (0.059/n)*\log(1/[M^+])$, where n is the number electrons transferred and $[M^+]$ is the concentration of the metal in solution.

The influence of an increase in the cyanide concentration is shown in Figures b.



Pourbaix Diagram Au/CN/ H_2O, high CN concentration

When comparing Figures 11 and 12, it becomes evident that the increase in the free cyanide concentration adversely affects the electrowinning process by changing the reduction potential of Au $(CN)^-_2$ to solid gold to more negative values. Typically a potential more negative than -0.65 V needs to be applied when the cyanide concentration is changed to 0.5 % whereas -0.56 V is required for 0.1 % cyanide.

2. Derivation for the cathodic reaction model

$E_{Ag} = -0.45 + 0.000086T \text{ Ln } [Ag(CN)_2^-]$

$E_{Au} = -0.63 + 0.000086T \text{ Ln } [Au(CN)_2^-]$

$E_{Cu} = -0.75 + 0.000086T \text{ Ln } [Cu(CN)_3^{2-}]$

$E_{Fe} = -0.77 + 0.000043T \text{ Ln } [Fe(CN)_6^{4-}]$

$E_{Ni} = -1.07 + 0.000043T \text{ Ln } [Ni(CN)_4^{2-}]$

The silver will be the first to be deposited at any temperature. The impurity copper will start co-depositing when E_{Au} will be equal or less than E_{Cu}. This will be the same for other impurities. Due the fact that the concentration of copper and iron are very low in the eluate, it will be advisable to avoid the nickel to co-depose with other elements. This will be done if the model provides the following relation: $E_{Au} > E_{Ni}$

$E_{Au} = -0.63 + 0.000086T \text{ Ln } [Au(CN)_2^-] > E_{Ni} = -1.07 + 0.000043T \text{Ln } [Ni(CN)_4^{2-}]$

$0.44 > 0.000043T \left(\text{Ln}[Ni(CN)_4^{2-}] - 2\text{Ln}[Au(CN)_2^-]\right)$

$$\frac{10233}{T} > \left(\text{Ln}\,[Ni(CN)_4^{2-}] - 2\,\text{Ln}\,[Au(CN)_2^-]\right) \quad (1)$$

Relation (1) describes the model that co-relates the concentration of nickel and gold and the temperature of the eluate in the electrowinning. This relation is limited to temperature above 75ºC, as any temperature below that will affect the kinetics of gold deposition

3. Derivation for kinetic model

This model will correlate the rate of deposition of different species during the electrowinning process. The following assumptions as made by Paul et al (1983) are:

- There is a plug flow in the cell i.e. that the back-mixing of solution does not occur.
- The cathode material is of uniform porosity and tortuosity
- The deposition rate of electroactive species within the bed is controlled by mass-transport to the cathode
- There is a steady-state flow in the cell

Paul et al (1983) postulated that the concentration, C_t , of electroactive species at any time, t, after the start of a multiple-pass electrowinning operations follows the relationship:

$C_t = C_o \exp(-QRt/V)$ (2)

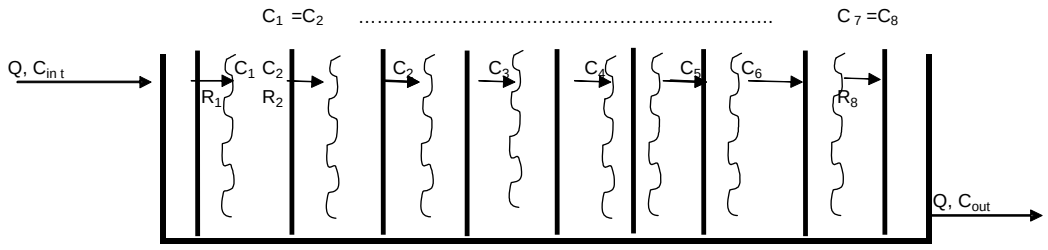
Where C_o is the concentration in time t=0, E is the single pass extraction, t, the time and V is the volume of the cell.

Stanley (1987) affirmed that the recovery of any species by electrodeposition is measured in terms of the extraction efficiency E and this is correlated to the concentrations of species by the relations: $R = (C_o - C_t)/ C_t$ (3) where C_o and C_t are the concentrations of electroactives species entering and leaving the electrowinning cells respectively

By replacing the E from (13) to (12), and re-arranging all terms of the relationship, one obtains

$\mathbf{Ln\ C_t + hC_tt = Ln\ C_o - Qt/V}$ **(4)** with $h = Q/ C_o$

After the establishment of the model that correlate the concentration of species at any time t in the cell, one has to establish the model that correlate the deposition rate during the electrowinning. Figure No 7 shows the sketch of the process:



Steel wool electrowinning cell

The mass balance of each species entering the cell will go through n = 8 cathodes in the cells with a constant flow rate Q and R_n the deposition rate for the specific cathode.

$C_{in}\,Q = R_1 + C_1\,Q$ (5)

$C_1\,Q = R_2 + C_2\,Q$ (6)

$C_2\,Q = R_3 + C_3\,Q$ (7)

$C_3\,Q = R_4 + C_4\,Q$ (8)

$C_4\,Q = R_5 + C_5\,Q$ (9)

$C_5\,Q = R_6 + C_6\,Q$ (10)

$C_6\,Q = R_7 + C_7\,Q$ (11)

$C_7\,Q = R_8 + C_{out}\,Q$ (12)

By replacing equation (12) in equation (11), one correlates the inlet and outlet in the cathode No8. By keep on doing the same replacement, one will find the following relations:

$C_7\,Q = R_8 + C_{out}\,Q$ (13)

$C_6\,Q = R_7 + R_8 + C_{out}\,Q$ (14)

$C_5\,Q = R_6 + R_7 + R_8 + C_{out}\,Q$ (15)

$C_4\,Q = R_5 + R_6 + R_7 + R_8 + C_{out}\,Q$ (16)

$C_3\,Q = R_4 + R_5 + R_6 + R_7 + R_8 + C_{out}\,Q$ (17)

$C_2\,Q = R_3 + R_4 + R_5 + R_6 + R_7 + R_8 + C_{out}\,Q$ (18)

$C_1\,Q = R_2 + R_3 + R_4 + R_5 + R_6 + R_7 + R_8 + C_{out}\,Q$ (19)

$C_{in}\,Q = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7 + R_8 + C_{out}\,Q$ (20)

Assuming the $R_n = R$, relation (20) will be

$C_{in}\,Q = nR + C_{out}\,Q$ (21)

Stanley (1987) emphasized that the deposition rate R is given by the $R = k_L A C_{nt}$ (22) where k_L is the mass-transfer coefficient, C_t is the concentration and A is the electrode area of each cathode.
By introducing (22) to (21) and re-arranging the terms, the relationship will become:

$C_{nt} = (C_{in} - C_{out})*Q / n\,k_L A$ (33)

Both relations (14) and (33) describe the kinetic model of each species of the electrolyte that enter the cell and provide their concentration and mass- transfer coefficient at any given time.
It is also evident that the increase of the deposition rate depends only on the electrode area.

4 Determination of model parameters

4.1 Flow rate and volume

The flow rate in the electrowinning varies between 25-35 m^3/ h, this is equivalent to 6.9- 8.3 l/h and the cell volume is 1.2 m^3.
Barbosa et al (2001) studied the performance evaluation of different reaction systems and have establish the mass transport coefficient (k_L) for gold deposition on a steel wool electrode to be $56*10^{-6}$ ms^{-1}

4.2 Calculation of the steel wool area A

The density of the steel wool is ρ_{steel}= 7000 kg/m^3 and the radium of the section wire is r = 140 μm.
$\rho = m/ \pi*L*r$
$m/L = 7000*3.14*(0.00014)^2$
$= 0.000431$ m/kg
This equates to $(0.000431 \text{ kg/m})^{-1} = 2320$ m/kg
With 3 kg of steel wool per cathode, this is equivalent to 2320*3= 6960 m of steel wool wire per cathode.
The steel wool area A is given by $2*\pi*L*r = 2*3.14*6960*o.00014 = 6.12$ m^2

5 Data for single pass rate and deposition rate for normal plant practice

1st test 14/11/2006

	Au Feed	Au Out	Ag Feed	Ag out	Cu Feed	Cu Out	Ni Feed	Ni out	Au	Ag	Cu	Ni
1 hour	320	150	389	89	42	41	450	450	53.13%	77.14%	2.38%	0.00%
2 hour	450	230	500	161	47	45	550	540	48.89%	67.78%	4.26%	1.82%
3 hour	675	250	611	239	46	35	620	615	62.96%	60.91%	23.91%	0.81%
4 hour	980	530	200	83	56	42	700	690	45.92%	58.33%	25.00%	1.43%
5 hour	1560	910	167	89	38	19	750	730	41.67%	46.67%	50.00%	2.67%
6 hour	1490	910	44	28	34	14	990	980	38.93%	37.50%	58.82%	1.01%
7 hour	1380	810	11	8	28	11	760	720	41.30%	30.00%	60.71%	5.26%
8 hour	1100	540			24	11	870	570	50.91%		54.17%	34.48%
9 hour	900	430			22	7	780	510	52.22%		68.18%	34.62%
10 hour	630	320			15	5	630	350	49.21%		66.67%	44.44%
11 hour	540	360			8	5	870	360	33.33%		37.50%	58.62%
12 hour	210	135					910	375	35.71%			58.79%
13 hour	110	65					860	320	40.91%			62.79%
14 hour	75	30					760	550	60.00%			27.63%
15 hour	55	30					810	360	45.45%			55.56%
16 hour	25	15					850	250	40.00%			70.59%
17 hour	10	7					830	275	30.00%			66.87%

2nd test 16/11/2006

	Au Feed	Au out	Ag Feed	Ag out	Cu Feed	Cu Out	Ni Feed	Ni out	Au	Ag	Cu	Ni
1 hour	300	240	494	106	80	75	825	825	20.00%	78.57%	6.25%	0.00%
2 hour	450	310	412	153	63	51	790	790	31.11%	62.86%	19.05%	0.00%
3 hour	920	430	647	247	76	46	820	810	53.26%	61.82%	39.47%	1.22%
4 hour	1345	780	424	153	56	29	970	950	42.01%	63.89%	48.21%	2.06%
5 hour	2010	1250	288	124	32	17	850	830	37.81%	57.14%	46.88%	2.35%
6 hour	1650	1150	153	73	27	11	720	710	30.30%	52.31%	59.26%	1.39%
7 hour	1590	1190	106	65	45	19	690	550	25.16%	38.89%	57.78%	20.29%
8 hour	1300	700	41	27	22	10	840	600	46.15%	34.29%	54.55%	28.57%
9 hour	1035	550			15	9	910	690	46.86%		40.00%	24.18%
10 hour	790	450			8	5	760	450	43.04%		37.50%	40.79%
11 hour	710	430			7	4	870	350	39.44%		42.86%	59.77%
12 hour	515	390					760	570	24.27%			25.00%
13 hour	410	290					870	450	29.27%			48.28%
14 hour	200	120					780	350	40.00%			55.13%
15 hour	150	70					630	290	53.33%			53.97%
16 hour	80	35					650	360	56.25%			44.62%
17 hour	25	15					750	320	40.00%			57.33%
	10	6					730	310	40.00%			57.53%

6. Data for single pass rate and deposition rate for improved plant practice: Reduction of elution time and electrowinning

3rd test 27/11/2006

	Au Feed	Au out	Ag Feed	Ag out	Cu Feed	Cu Out	Ni Feed	Ni out	Au	Ag	Cu	Ni
1 hour	550	220	450	120	82	76	620	615	60.00%	73.33%	7.32%	0.81%
2 hour	1000	600	380	130	66	52	750	750	40.00%	65.79%	21.21%	0.00%
3 hour	1284	940	500	230	77	38	780	760	26.79%	54.00%	50.65%	2.56%
4 hour	1350	1160	260	110	52	21	810	800	14.07%	57.69%	59.62%	1.23%
5 hour	1600	1270	130	75	36	15	810	740	20.63%	42.31%	58.33%	8.64%
6 hour	1340	1040	70	44	22	11	930	870	22.39%	37.14%	50.00%	6.45%
7 hour	850	580	20	14	15	8	790	710	31.76%	30.00%	46.67%	10.13%
8 hour	750	310			8	3	940	720	58.67%		62.50%	23.40%
9 hour	640	230					850	350	64.06%			58.82%
10 hour	460	214					890	210	53.48%			76.40%
11 hour	390	105					830	350	73.08%			57.83%
12 hour	340	110					730	360	67.65%			50.68%
13 hour	160	48					750	310	70.00%			58.67%
14 hour	80	33					810	280	58.75%			65.43%
15 hour	50	19					850	300	62.00%			64.71%

7. Tracking elements during different conditions in the elution

	TRACKING THE ELEMENTS															
	8-May	**9-May**	**10-May**	**11-May**	**12-May**	**13-May**	**14-May**	**15-May**	**16-May**	**17-May**	**18-May**	**19-May**	**20-May**	**21-May**	**22-May**	**23-May**
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
pH inlet	12.27	12.71	12.87	12.98	12.93	12.17	12.24	12.77	12.13	12.45	13.76	12.71	13.49	12.09	12.87	12.62
pH outlet	12.71	12.88	12.83	13.07	13	12.38	1.27	12.89	13.5	12.95	13.96	12.71	12.98	12.05	12.85	12.58
Free NaOH	2.1	2.1	2.1	2.1	2	2.5	2.3	2.2	2.2	2.1	2.2	2.2	2.2	2	2.2	2.2
Temp. in	**122**	**120**	**121**	**129**	**131**	**125**	**122**	**124**	**128**	**131**	**125**	**129**	**134**	**129**	**119**	**118**
Temp. out	**123**	**125**	**130**	**128**	**132**	**121**	**117**	**119**	**127**	**129**	**120**	**110**	**124**	**128**	**118**	**118**
Loaded C Zn (kg/t)	0.125	0.136	0.124	0.168	0.178	0.183	0.125	0.133	0.157	0.19	0.134	0.129	0.138	0.175	0.136	0.154
Loaded C Fe (kg/t)	0.351	0.475	0.621	0.741	0.234	0.334	0.345	0.316	0.824	0.45	0.425	0.161	0.378	0.753	0.746	0.609
Loaded C Ni (kg/t)	7	6.9	6.96	6.6	6.83	6.75	6.89	8.64	7.61	8.20	7	6.9	6.96	6.12	6.83	6.645
Loaded C Cu (kg/t)	0.4	0.3	0.40	0.25	0.4	0.61	0.45	0.395	0.457	0.65	0.4	0.3	0.4	0.10	0.4	0.516
Looded C Ag (kg/t)	2.3	2.1	1.60	1.5000	1.7	1.4	2.2	2.3	1.6	1.8	2.01	1.3	1.5	1.200	1.3	1.4
Eluted C Zn (kg/t)	0.124	0.135	0.12	0.1650	0.178	0.178	0.121	0.132	0.154	0.17	0.133	0.125	0.133	0.173	0.131	0.141
Eluted C Fe (kg/t)	0.125	0.019	0.0400	0.3040	0.231	0.034	0.322	0.215	0.241	0.10	0.11	0.13	0.1	0.1	0.12	0.305
Eluted C Ni (kg/t)	6.4	5.8	5.40	6.1	6.2	6.54	6.75	7.15	6.12	6.23	6.4	5.8	5.40	5.1	6.2	5.945
Eluted C Cu (kg/t)	0.026	0.016	0.014	0.1010	0.023	0.031	0.024	0.013	0.009	0.0	0.026	0.016	0.014	0.02	0.023	0.033
Eluted Ag Co (kg/t)	0.3	0.3	0.2	0.5	0.2	0.1	0.4	0.1	0.3	0.5	0.4	0.2	0.3	0.4	0.2	0.4
Eluant Zn (kg/t)	0.4	0.2	0.5	0.8	0.1	0.2	0.3	0.1	0.2	0.11	0.131	0.128	0.137	0.169	0.129	0.9
Eluant Fe (mg/l)	0.1	0.1	0.1	0.1	0.3	0.1	0.2	0.1	0.2	0.3	0.1	0.1	0.1	0.1	0.1	0.5
Eluant Ni (mg/l)	370	380	350	400	320	300	350	370	630	410	450	350	400	370	640	880
Eluant Cu (mg/l)	2.2	1.6	3.40	2	1.9	2.3	2.2	2.2	2.5	1.7	1.6	2	2.5	2.2	1.9	2.2
Eluant Ag (g/l)	0.2	0.8	0.1	0.3	0.5	0.8	0.5	0.8	0.5	0.8	0.8	0.3	0.4	0.3	0.8	0.8
Eluant Co (mg/l)	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.8	0.8	0.6	0.5	0.6	0.6	0.5	0.6	1.1
Eluate Zn (mg/l)	0.4	0.2	0.6	0.4	0.3	0.5	0.4	0.6	0.7	0.6	0.8	0.9	0.4	0.6	0.5	0.6
Eluate Fe (mg/l)	0.1	0.1	0.1	0.1	0.3	0.2	0.2	0.1	0.2	0.4	0.1	0.1	0.3	0.1	0.1	0.4
Eluate Ni (mg/l)	380	460	390	420	340	410	550	490	750	540	553	550	620	450	750	990
Eluate Cu (mg/l)	3.8	2.4	4.8	3	4	3.7	4.4	3.1	3.8	3.6	2.9	3.5	4.3	3.4	2.8	4.1
Eluate Ag (mg/l)	2	1.9	2.3	2.2	2.2	2.5	1.7	1.6	2	2.5	2.2	1.9	2.2	2	1.1	1.3
Eluate Co (mg/l)	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.8	0.6	0.5	0.6	0.5	0.5	0.6	1
Finesse (%)		78.63		79.05			83.2		79.5		77.18			81.25		81.13
Loaded Carbon (g/t)	850	660	897	880	670	780	490	1060	1200	923	958	910	910	2500	2150	3200
Eluted Carbon (g/t)	150	120	98	150	104	90	115	185	180	140	180	156	178	300	300	270
Elution efficiency (%)	82.4	81.8	89.1	83.0	84.5	88.5	76.5	82.5	85.0	84.8	81.2	82.9	80.4	88.0	86.0	91.6

CHANGE OF FLOW RATE

	24-May	25-May	26-May	27-May	28-May	29-May	30-May	31-May	1-Jun	2-Jun	3-Jun	4-Jun	5-Jun	6-Jun	7-Jun	8-Jun
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	30	30	35	35	35	35	35	35	35	35	35	35	35	35	35	35
pH inlet	10.88	11.32	13.23	13.81	12.08	12.85	12.86	12.46	12.87	12.93	13.71	12.89	12.86	12.94	13.07	12.89
pH outlet	11.71	12.81	13.84	13.92	13.11	12.86	12.8	12.51	12.94	12.87	12.37	12.93	12.69	12.98	13.26	12.93
Free NaOH	2.1	2.1	2.3	2.3	2.2	2.2	2.1	2.1	2.1	2.2	2.1	2	2	2.3	2	2.1
Temp. in	**128**	**132**	**136**	**133**	**132**	**129**	**121**	**127**	**132**	**125**	**135**	**129**	**126**	**123**	**129**	**130**
Temp. out	**132**	**122**	**128**	**121**	**121**	**124**	**133**	**130**	**132**	**120**	**123**	**128**	**123**	**126**	**130**	**131**
Loaded C Zn (kg/t)	0.128	0.127	0.145	0.128	0.136	0.156	0.147	0.163	0.162	0.163	0.124	0.159	0.148	0.164	0.168	0.159
Loaded C Fe (kg/t)	0.308	0.268	0.759	0.308	0.458	1.26	0.744	0.733	0.743	0.744	0.621	0.9	2.15	1.02	0.741	0.924
Loaded C Ni (kg/t)	6.087	7.04	6.087	6.087	7.582	8.693	7.84	7.85	7.84	7.847	6.96	8.2	6.648	7.277	6.6000	6.783
Loaded C Cu (kg/t)	0.606	0.25	0.467	0.606	0.512	0.44	0.431	0.439	0.431	0.431	0.40	0.4	0.426	0.398	0.2500	0.339
Looded C Ag (kg/t)	2.1	1.9	0.6	0.4	2.01	1.5	1.4	0.9	1.9	1.6	1.2	0.2	1.4	1.7	2.5	0.8
Eluted C Zn (kg/t)	0.122	0.119	0.143	0.122	0.148	0.156	0.139	0.119	0.129	0.131	0.12	0.138	0.140	0.161	0.1650	0.14
Eluted C Fe (kg/t)	0.1	0.1	0.369	0.1	0.100	0.1	0.178	0.152	0.179	0.1	0.0400	0.100	0.963	0.306	0.3040	0.521
Eluted C Ni (kg/t)	4.718	4.851	5.742	4.718	6.852	7.684	6.988	6.98	6.988	5.779	5.40	7.095	5.963	6.217	6.1000	6.664
Eluted C Cu (kg/t)	0.017	0.023	0.026	0.017	0.028	0.023	0.03	0.029	0.03	0.016	0.014	0.018	0.230	0.280	0.1010	0.024
Eluted Ag Co (kg/t)	0.8	1.1	0.4	0.3	0.4	0.10	0.4	0.5	0.7	0.1	0.8	2.3	0.2	0.8	1.1	0.9
Eluant Zn (kg/t)	0.5	0.7	0.9	0.8	2.3	1	0.9	1	1.2	1.1	0.9	1.1	1.2	0.7	0.1	0.8
Eluant Fe (mg/l)	0.5	0.6	0.5	0.6	0.7	0.7	0.3	0.4	0.4	0.4	0.4	0.8	0.9	0.6	0.3	0.1
Eluant Ni (mg/l)	410	550	450	400	330	750	460	470	380	410	490	970	970	550	320	400
Eluant Cu (mg/l)	3.2	2.9	3.9	3.5	6.1	5.8	1.6	1.2	0.2	1.4	1.7	2.5	0.8	2.9	1.9	2
Eluant Ag (g/l)	1.2	0.4	0.1	0.3	0.5	0.4	0.2	0.3	0.4	0.2	0.4	0.8	1.1	0.4	0.3	0.4
Eluant Co (mg/l)	1.1	1.3	1	1.2	1.5	1.3	1.4	1.6	1.7	1.7	1.5	1.5	1.6	1.3	0.8	0.7
Eluate Zn (mg/l)	0.4	0.6	0.8	0.7	2.2	0.9	0.9	1.1	1.3	1.3	1.1	1	1.1	0.6	0.4	0.5
Eluate Fe (mg/l)	0.4	0.5	0.4	0.5	0.5	0.6	0.3	0.4	0.4	0.5	0.5	0.9	0.8	0.5	0.4	0.3
Eluate Ni (mg/l)	400	530	430	630	300	980	530	430	680	740	560	910	980	560	330	650
Eluate Cu (mg/l)	3.5	2.3	5.7	9.1	7.7	6.1	2.2	1.8	0.2	2.7	3	1.4	0.5	2.3	2.6	3.1
Eluate Ag (mg/l)	0.6	3.1	3.7	1.9			2.7	3.7	1.6	1.4	2.9	2.7	3.7	0.8	1.3	1.5
Eluate Co (mg/l)	1	1.1	0.9	1.1	1.5	1.2	1.4	1.7	1.8	1.8	1.6	1.5	1.5	1.1	0.8	0.7
Finesse (%)		82		74.98			74.17		77.88			77.31		75.13		77.87
Loaded Carbon (g/t)	3100	990	640	640	353	710	760	1550	1650	1341	2400	2400	1000	890	720	1300
Eluted Carbon (g/t)	520	170	230	330	150	260	270	340	250	194	660	560	280	260	190	280
Elution efficiency (%)	83.2	82.8	64.1	48.4	57.5	63.4	64.5	78.1	84.8	85.5	72.5	76.7	72.0	70.8	73.6	78.5

CHANGE OF FLOW R

	9-Jun	10-Jun	11-Jun	12-Jun	13-Jun	14-Jun	15-Jun	16-Jun	17-Jun	18-Jun	19-Jun	20-Jun	21-Jun	22-Jun	23-Jun	24-Jun
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	35	35	35	35	35	35	35	35	35	35	25	25	25	25	25	25
pH inlet	12.86	12.48	12.48	12.63	12.87	13.12	12.88	12.89	12.96	12.86	12.54	12.98	13.01	12.48	12.3	12.41
pH outlet	12.83	12.48	12.4	12.84	12.89	12.05	12.82	12.87	12.92	12.79	12.51	12.97	12.81	12.43	12.38	12.36
Free NaOH	2	2.2	2.2	2.1	2.1	2.2	2.1	2	2.1	2.2	2.2	2.1	2.2	2.1	1.8	2.2
Temp. in	**120**	**125**	**120**	**129**	**126**	**133**	**130**	**128**	**128**	**123**	**128**	**128**	**129**	**110**	**104**	**100**
Temp. out	**121**	**128**	**122**	**129**	**124**	**129**	**129**	**126**	**126**	**122**	**127**	**124**	**123**	**116**	**115**	**126**
Loaded C Zn (kg/t)	0.161	0.136	0.18	0.141	0.137	0.142	0.139	0.14	0.124	0.149	0.174	0.134	0.164	0.261	0.183	0.178
Loaded C Fe (kg/t)	0.913	0.475	0.606	1.647	0.841	0.845	1.65	1.85	0.621	1.89	0.446	0.526	1.133	0.668	0.823	0.234
Loaded C Ni (kg/t)	7.499	6.9	7.739	6.88	6.969	6.656	7.549	6.185	6.96	7.558	7.382	6.311	7.32	6.981	7.162	6.83
Loaded C Cu (kg/t)	0.192	0.3	0.327	0.263	0.316	0.25	0.35	0.308	0.40	0.462	0.359	0.462	0.472	0.486	0.525	0.541
Looded C Ag (kg/t)	2.9	1.9	2	1.3	1.3	1	1.2	1.5	1.3	1.4	1.6	1.7	1.7	1.5	1.5	1.6
Eluted C Zn (kg/t)	0.161	0.135	0.16	0.14	0.136	0.13	0.129	0.111	0.12	0.129	0.163	0.129	0.128	0.136	0.137	0.178
Eluted C Fe (kg/t)	0.100	0.019	0.508	0.982	0.839	0.469	1.45	0.687	0.04	0.602	0.446	0.423	0.411	0.408	0.553	0.231
Eluted C Ni (kg/t)	6.295	5.8	6.71	6.276	5.696	6.25	7.128	6.119	5.40	6.37	4.895	4.184	5.716	4.619	5.472	5.2
Eluted C Cu (kg/t)	0.026	0.016	0.021	0.021	0.052	0.06	0.33	0.029	0.014	0.025	0.023	0.22	0.03	0.031	0.096	0.023
Eluted Ag Co (kg/t)	0.9	0.4	0.1	0.5	0.1	0.2	0.4	0.3	0.3	0.2	0.5	0.2	0.1	0.4	0.1	0.3
Eluant Zn (kg/t)	2.3	0.2	0.8	1.1	0.9	0.9	0.4	0.1	0.5	0.3	0.4	0.2	0.5	0.8	0.1	0.8
Eluant Fe (mg/l)	690	0.1	0.1	0.7	0.4	0.3	2.3	1.2	0.1	1.4	1.6	1.1	1.3	1.6	1.1	0.1
Eluant Ni (mg/l)	3.1	380	400	550	490	460	690	280	350	290	360	510	380	520	380	400
Eluant Cu (mg/l)	1.3	4.6	2	0.6	1.7	1.6	1.3	1.9	3.40	0.6	0.7	3.1	2.1	3.7	3.1	2
EluantAg (g/l)	0.5	0.6	0.8	0.7	0.7	0.6	0.8	1.5	1.3	0.8	0.6	0.7	0.1	0.5	0.1	0.2
Eluant Co (mg/l)	0.4	0.7	0.7	2.9	1.5	1.4	0.4	0.6	0.7	0.6	0.7	0.5	0.6	0.8	0.7	0.7
Eluate Zn (mg/l)	2.3	0.2	0.4	1.3	1.1	0.9	2.3	0.1	0.6	0.3	0.3	0.2	0.5	0.2	0.1	0.4
Eluate Fe (mg/l)	760	0.1	0.1	0.6	0.4	0.3	2.3	1.2	0.1	1.4	1.5	0.9	1.2	1.6	1.4	0.1
Eluate Ni (mg/l)	3.8	480	420	570	510	560	760	390	390	340	690	950	820	970	850	720
Eluate Cu (mg/l)	0.8	0.1	3	2.1	3	2.2	0.8	4.8	2.8	1.2	1.1	4.2	3.4	5.4	3.1	3
Eluate Ag (mg/l)	1.6	1.3	1.2	1.4	2.2	2.3	1.6	1.8	2.01	1.3	1.5	1.2	2.7	2.9	2.00	3.7
Eluate Co (mg/l)	0.6	0.4	0.7	2.3	1.6	1.4	0.6		0.7	0.6	0.7	0.5	0.7	0.8		0.7
Finesse (%)			78.87		74.24		75.64			75.39		70.77		73.97		
Loaded Carbon (g/t)	680	1100	1100	910	1500	710	1550	1000	980	980	980	1420	960	950	850	890
Eluted Carbon (g/t)	180	350	330	240	450	340	280	240	380	380	190	250	80	150	120	170
Elution efficiency (%)	73.5	68.2	70.0	73.6	70.0	52.1	81.9	76.0	61.2	61.2	80.6	82.4	91.7	84.2	85.9	80.9

Cleaned No2 Eluant tank

	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	25	25	25	35	35	30	30	30	30	30	30	30	30	30	30	30
pH inlet	12.87	12.54	12.14	12.39	12.93	12.68	12.1	13.52	13.45	12.86	12.93	12.41	12.46	12.94	12.99	12.95
pH outlet	12.83	12.56	11.99	12.36	13	12.5	12.2	13.05	13.32	12.69	12.89	12.45	12.4	12.89	12.96	12.89
Free NaOH	2.1	2.1	2.1	2.2	2	2	2	2.1	2.4	2.1	2	2.1	2	2.2	2.1	2.1
Temp. in	**121**	**100**	**112**	**114**	**131**	**120**	**128**	**127**	**129**	**130**	**131**	**116**	**129**	**131**	**130**	**131**
Temp. out	**130**	**132**	**126**	**127**	**132**	**126**	**127**	**128**	**128**	**131**	**128**	**124**	**126**	**130**	**131**	**129**
Loaded C Zn (kg/t)	0.151	0.123	0.139	0.156	0.668	0.178	0.724	0.888	0.139	0.161	0.18	0.139	0.134	0.149	0.123	0.668
Loaded C Fe (kg/t)	0.825	0.205	6.939	1.26	1.246	0.234	11.89	0.301	1.65	0.913	0.606	1.65	0.526	0.768	0.205	1.246
Loaded C Ni (kg/t)	6.991	6.703	6.612	8.693	5.63	6.83	7.033	5.474	7.549	7.499	7.739	7.549	6.311	7.28	6.703	5.63
Loaded C Cu (kg/t)	0.439	0.435	0.554	0.45	0.037	0.4	0.414	0.061	0.35	0.192	0.327	0.35	0.462	0.624	0.435	0.037
Looded C Ag (kg/t)	1.2	1.4	2.2	2.3	1.6	1.8	2.01	1.3	1.5	1.200	1.3	1.4	2.1	1.9	0.6	0.4
Eluted C Zn (kg/t)	0.124	0.121	0.135	0.156	0.122	0.178	0.142	0.13	0.129	0.161	0.16	0.129	0.129	0.139	0.121	0.122
Eluted C Fe (kg/t)	0.329	0.169	3.112	0.1	1.102	0.231	6.821	0.086	1.45	0.100	0.508	1.45	0.423	0.526	0.169	1.102
Eluted C Ni (kg/t)	5.144	4.919	4.262	7.684	3.292	6.2	4.568	3.126	7.128	6.295	6.71	7.128	4.184	5.398	4.919	3.292
Eluted C Cu (kg/t)	0.019	0.024	0.022	0.021	0.025	0.023	0.061	0.016	0.33	0.026	0.021	0.33	0.22	0.038	0.024	0.025
Eluted Ag Co (kg/t)	0.4	0.2	0.3	0.4	0.2	0.2	0.6	0.4	0.3	0.3	0.4	0.5	0.7	0.2	0.1	0.4
Eluant Zn (kg/t)	0.1	0.5	0.4	0.8	0.3	0.8	0.8	0.3	0.5	0.3	0.4	0.1	0.3	0.1	0.5	0.8
Eluant Fe (mg/l)	0.3	2.2	2.3	1.6	0.8	0.1	1.6	0.8	0.1	1.4	1.6	0.2	0.8	1	2.2	1.6
Eluant Ni (mg/l)	320	860	590	520	600	400	520	600	350	290	360	500	600	600	860	520
Eluant Cu (mg/l)	1.9	0.6	2.1	2.7	2.9	2.00	3.7	2.9	3.40	0.6	0.7	2.5	2.9	3.7	0.6	2.7
Eluant Ag (g/l)	0.3	0.3	0.2	2	0.6	2.7	0.6	0.2	0.8	0.1	0.3	0.5	0.8	0.5	0.8	0.5
Eluant Co (mg/l)	0.8	1.5	1.3	0.8	0.6	0.7	0.8	0.6	0.7	0.6	0.7	0.6	0.6	0.7	1.5	0.8
Eluate Zn (mg/l)	0.3	0.5	0.4	0.2	0.3	0.4	0.2	0.3	0.6	0.3	0.3	0.3	0.3	0.3	0.5	0.2
Eluate Fe (mg/l)	0.3	2.4	2.3	1.6	1.2	0.1	1.6	1.2	1.3	1.3	1.4	0.4	1.2	1.7	2.4	1.6
Eluate Ni (mg/l)	840	910	760	570	670	420	570	670	400	350	380	550	670	690	910	570
Eluate Cu (mg/l)	4	1.3	3.8	5.4	3.8	3	5.4	3.8	2.8	1.2	1.1	3	3.8	4.3	1.3	5.4
Eluate Ag (mg/l)	2.10	0.6	0.7	2.5	2.9	1.7	1.8	2.7	3.40	2	1.9	2.3	2.2	2.2	2.5	1.7
Eluate Co (mg/l)	0.7	1.5	0.8	0.8	0.6	0.7	0.8	0.6	0.7	0.6	0.7	0.6	0.6	0.7	1.5	0.8
Finesse (%)			70.8				80.12		89.71			77.64		72.58		
Loaded Carbon (g/t)	1250	1800	2050	680	730	730	870	1200	2150	1750		1250	1250	670	2050	
Eluted Carbon (g/t)	140	90	370	220	170	180	140	360	160	60		240	240	340	720	
Elution efficiency (%)	88.8	95.0	82.0	67.6	76.7	75.3	83.9	70.0	92.6	96.6		80.8	80.8	49.3	64.9	

Change temperature close 120

	12-Jul	13-Jul	14-Jul	15-Jul	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul	1-Aug
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
pH inlet	12.56	12.68	12.91	12.92	12.86	12.74	12.97	12.94	12.96	12.8	12.3	12.94	12.89	12.41	12.65	12.89	12.94	12.96	11.36	11.45	10.95
pH outlet	12.8	12.64	12.88	12.88	12.91	12.45	12.88	12.86	12.94	12.9	14.56	12.9	12.86	12.36	12.6	12.94	12.86	12.94	11.23	11.21	10.45
Free NaOH	2.2	2.2	2.1	2.1	2.1	2.2	2.1	2.2	2	2	2.2	2.2	2.1	2.2	2.2	2.2	2.2	2	1.9	1.9	1.6
Temp. in	**106**	**130**	**130**	**130**	**110**	**127**	**119**	**120**	**120**	**121**	**121**	**132**	**130**	**119**	**118**	**121**	**120**	**120**	**129**	**120**	**120**
Temp. out	**132**	**132**	**128**	**125**	**131**	**135**	**120**	**116**	**120**	**80**	**124**	**131**	**131**	**126**	**119**	**123**	**117**	**120**	**123**	**120**	**126**
Loaded C Zn (kg/t)	0.131	0.147	1.011	0.139	1.013	0.156	0.13	0.15	0.129	0.157	0.164	0.123	0.129	0.129	0.129	0.157	0.16	0.129	0.164	0.129	0.178
Loaded C Fe (kg/t)	0.531	0.511	0.942	1.65	3.202	1.09	1.338	0.826	0.666	1.211	1.133	0.468	0.583	0.38	0.666	1.211	0.826	0.667	1.133	0.666	0.234
Loaded C Ni (kg/t)	6.589	6.735	6.735	7.549	3.502	7.189	6.759	6.764	6.48	6.807	7.32	6.758	6.912	5.582	6.48	6.807	6.74	6.52	6.32	6.251	5.31
Loaded C Cu (kg/t)	0.435	0.374	0.374	0.35	0.894	0.42	0.368	0.348	0.377	0.416	0.472	0.389	0.369	0.419	0.377	0.416	0.351	3.77	0.472	0.377	0.541
Looded C Ag (kg/t)	2.01	1.5	1.4	0.9	1.9	1.4	1.5	3.1	1.5	2.1	1.6	1.4	1.5	1.8	1.6	1.1	1.2	1.5	1.4	1.3	1.5
Eluted C Zn (kg/t)	0.01	0.143	0.141	0.129	0.989	0.156	0.123	0.144	0.116	0.125	0.116	0.108	0.122	0.99	0.125	0.108	0.144	0.116	0.128	0.116	0.178
Eluted C Fe (kg/t)	0.244	0.317	0.815	0.508	0.513	0.585	0.881	0.556	0.283	0.442	0.283	0.406	0.517	0.241	0.442	0.406	0.556	0.287	0.411	0.283	0.231
Eluted C Ni (kg/t)	0.011	6.128	3.068	6.71	3.068	6.98	5.619	6.553	6.169	6.626	6.169	5.66	5.276	5.282	6.626	5.66	6.553	6.185	5.716	6.169	5.2
Eluted C Cu (kg/t)	0.017	0.028	0.059	0.021	0.059	0.019	0.135	0.017	0.377	0.016	0.377	0.024	0.021	0.025	0.016	0.024	0.017	0.377	0.03	0.377	0.023
Eluted Ag Co (kg/t)	0.8	0.9	0.8	0.7	0.3	0.5	0.3	0.4	0.1	0.3	0.1	0.5	0.8	0.8	0.5	0.3	0.4	0.2	0.5	0.8	0.1
Eluant Zn (kg/t)	0.8	0.3	0.5	0.8	0.3	0.1	0.2	0.9	1.2	0.8	1.1	0.4	0.3	0.2	0.8	0.1	0.3	0.5	0.8	0.5	0.8
Eluant Fe (mg/l)	1.6	1.4	1.3	1.6	0.8	0.2	0.1	0.3	0.9	0.1	0.7	2.3	1.4	1.1	1.6	0.3	1.4	1.3	0.1	2.2	1.6
Eluant Ni (mg/l)	520	290	380	520	600	500	300	460	970	400	550	690	290	510	520	320	290	380	400	860	520
Eluant Cu (mg/l)	3.7	0.6	2.1	3.7	2.9	2.5	2.3	1.6	1.5	2	1.1	1.3	0.6	3.1	3.7	1.9	0.6	2.1	2	0.6	2.7
Eluant Ag (g/l)	0.8	0.8	0.3	0.4	0.3	0.8	0.8	1.2	0.4	0.3	0.5	0.3	0.4	0.1	0.3	0.1	0.5	0.8	0.8	0.5	0.3
Eluant Co (mg/l)	0.8	0.6	0.6	0.8	0.6	0.6	0.8	1.4	1.6	0.7	2.9	0.4	0.6	0.5	0.8	0.8	0.6	0.6	0.7	1.5	0.8
Eluate Zn (mg/l)	0.2	0.3	0.5	0.2	0.3	0.3	0.5	0.9	1.1	0.5	1.3	2.3	0.3	0.2	0.2	0.3	0.3	0.5	0.4	0.5	0.2
Eluate Fe (mg/l)	1.6	1.3	1.2	1.6	1.2	0.4	0.2	0.3	0.8	0.3	0.6	2.3	1.4	0.9	1.6	0.3	1.4	1.2	0.1	2.4	1.6
Eluate Ni (mg/l)	570	350	820	570	670	550	410	530	980	650	570	760	340	950	970	840	340	820	720	910	570
Eluate Cu (mg/l)	5.4	1.2	3.4	5.4	3.8	3	3.7	2.2	0.5	3.1	2.1	0.8	1.2	4.2	5.4	4	1.2	3.4	3	1.3	5.4
Eluate Ag (mg/l)	1.6	2	2.5	2.2	1.9	2.7	3.7	1.6	1.4	2.9	2.7	3.7	0.8	1.3	1.4	1.3	1.5	1.8	1.4	1.1	1.5
Eluate Co (mg/l)	0.8	0.6	0.7	0.8	0.6	0.6	0.8	1.4	1.5	0.7	2.3	0.6	0.6	0.5	0.8	0.7	0.6	0.7	0.7	1.5	0.8
Finesse (%)	81.45		83.1			82.98		85.23			86.12		81.57			84.87		82.4		83.21	
Loaded Carbon (g/t)	1950	780	790	920	1230	1050	1600	860	640	660	660	720	740	730	480	690	790	910	910	1400	930
Eluted Carbon (g/t)	280	120	170	170	140	90	370	220	170	190	161	240	199		147		150		295		156
Elution efficiency (%)	73.35			78.56		74.84		75.24			75.66		73.06		69.3		81		67.57		83.2

	2-Aug	3-Aug	4-Aug	5-Aug	6-Aug	7-Aug	8-Aug	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug	15-Aug	16-Aug	17-Aug
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
pH inlet	10.25	10.02	10.74	10.56	10.62	10.33	10.25	10.24	10.57	12.96	10.45	10.16	12.86	12.36	12.6	12.94
pH outlet	10.65	10.23	10.45	10.16	10.24	10.68	10.11	10.18	10.84	12.94	10.62	10.33	12.91	12.92	12.86	12.74
Free NaOH	1.5	1.4	1.4	1.5	1.8	1.6	1.5	1.7	1.6	1.8	1.4	1.4	1.5	1.8	1.6	1.5
Temp. in	**124**	**126**	**119**	**122**	**124**	**125**	**120**	**121**	**123**	**120**	**120**	**124**	**126**	**119**	**122**	**130**
Temp. out	**127**	**125**	**124**	**129**	**120**	**123**	**116**	**119**	**119**	**120**	**119**	**117**	**124**	**124**	**131**	**131**
Loaded C Zn (kg/t)	0.156	0.139	0.139	0.668	1.011	1.013	0.15	0.164	0.157	0.129	0.15	0.18	0.141	0.137	0.142	0.139
Loaded C Fe (kg/t)	1.26	1.65	1.65	1.246	0.942	3.202	0.826	1.133	1.211	0.667	0.826	0.606	1.647	0.841	0.845	1.65
Loaded C Ni (kg/t)	7.145	7.549	7.549	5.63	6.735	3.502	6.764	7.32	6.807	6.52	6.764	7.739	6.88	6.969	6.656	7.549
Loaded C Cu (kg/t)	0.45	0.35	0.35	0.37	0.374	0.894	0.348	0.472	0.416	3.77	0.348	0.327	0.263	0.316	0.25	0.35
Looded C Ag (kg/t)	1.8	1.4	1.1	1.5	1.6	1.8	1.4	1.4	1.4	1.7	1.4	2	1.3	1.3	1	1.2
Eluted C Zn (kg/t)	0.156	0.129	0.129	0.122	0.141	0.989	0.144	0.116	0.108	0.116	0.144	0.16	0.14	0.136	0.13	0.129
Eluted C Fe (kg/t)	0.1	1.45	1.45	1.102	0.815	0.513	0.556	0.283	0.406	0.287	0.556	0.508	0.982	0.839	0.469	1.45
Eluted C Ni (kg/t)	7.684	7.542	7.394	5.61	6.689	3.068	6.589	7.24	6.746	6.473	6.589	6.71	6.276	5.696	6.25	7.128
Eluted C Cu (kg/t)	0.12	0.19	0.33	0.21	0.122	0.231	0.125	0.377	0.216	0.256	0.19	0.3	0.1	0.3	0.4	0.1
Eluted Ag Co (kg/t)	0.8	0.1	0.1	0.5	0.4	0.8	0.3	0.1	0.5	0.3	0.1	0.8	0.4	0.8	0.1	0.1
Eluant Zn (kg/t)	0.5	0.8	0.8	0.3	0.4	0.3	0.8	0.8	1.2	0.4	0.8	0.5	0.4	0.5	0.8	0.8
Eluant Fe (mg/l)	2.2	1.6	1.6	1.4	1.6	0.8	1.6	1.6	0.9	2.3	1.6	2.2	1.6	2.2	1.6	1.6
Eluant Ni (mg/l)	860	520	520	290	360	600	520	520	970	690	520	540	560	630	320	290
Eluant Cu (mg/l)	0.6	2.7	3.7	1.6	1.4	2.9	2.7	3.7	0.8	1.3	2.7	0.6	2.1	2	0.6	2.7
EluantAg (g/l)	0.4	0.2	0.8	0.8	0.5	0.3	0.4	0.8	0.5	0.9	0.4	0.5	0.8	0.8	0.5	0.3
Eluant Co (mg/l)	1.5	0.8	0.8	0.6	0.7	0.6	0.8	0.8	1.6	0.4	1.5	0.6	0.6	0.7	1.5	0.8
Eluate Zn (mg/l)	0.5	0.2	0.2	0.3	0.3	0.3	0.2	0.2	1.1	2.3	0.5	0.3	0.5	0.4	0.5	0.2
Eluate Fe (mg/l)	2.4	1.6	1.6	1.3	1.4	1.2	1.6	1.6	0.8	2.3	2.4	1.4	1.2	0.1	2.4	1.6
Eluate Ni (mg/l)	910	530	530	300	380	620	540	530	980	700	550	410	530	980	650	570
Eluate Cu (mg/l)	1.3	3.5	4.4	0.8	1.1	3.4	3.5	4.5	0.11	1.9	1.3	5.4	1.3	3.5	4.4	0.8
Eluate Ag (mg/l)	1.6	1.8	1.4	1.4	1.4	1.7	1.9	1.1	1.3	1.2	1.1	1.5	1.6	1.8	1.4	1.4
Eluate Co (mg/l)	1.5	0.8	0.8	0.6	0.7	0.6	0.8	0.8	1.5	0.6	1.5	0.8	1.5	0.8	0.8	0.6
Finesse (%)	80.95			82.35		84.16			83.52		86.23			83.13		84.25
Loaded Carbon (g/t)	1000	680	680	890	750	820	900	650	860	840	1120	1020	1290	890	880	670
Eluted Carbon (g/t)			112	150	110	140	151	90	150	90	210	190	190	70	160	90
Elution efficiency (%)			83.5	83.1	85.3	82.9	77.5	86.2	82.6	89.3	81.3	81.4	85.3	92.1	81.8	86.6

	19-Aug	20-Aug	21-Aug	22-Aug	23-Aug	24-Aug	25-Aug	26-Aug	27-Aug	28-Aug	29-Aug	30-Aug	31-Aug
Elution time (hour)	18	18	18	18	18	18	18	18	18	18	18	18	18
Flow (m^3/h)	30	30	30	30	30	30	30	30	30	30	30	30	30
pH inlet	12.45	13.25	13.56	14.56	12.9	12.3	12.94	12.89	12.41	12.65	12.89	12.94	12.96
pH outlet	12.94	12.96	12.45	12.88	12.86	12.94	12.9	13.56	12.9	11.21	12.45	12.98	12.43
Free NaOH	1.6	1.8											
Temp.in	**80**	**126**	**120**	**119**	**122**	**124**	**125**	**120**	**121**	**123**	**120**	**120**	
Temp.out	**119**	**119**	**117**	**124**	**126**	**119**	**127**	**125**	**124**	**129**	**120**	**123**	**116**
Loaded C Zn (kg/t)	0.124	0.149	0.174	0.139	1.013	0.156	0.13	0.15	0.129	0.139	0.668	1.011	1.013
Loaded C Fe (kg/t)	0.621	1.89	0.446	1.65	3.202	1.09	1.338	0.826	0.666	1.65	1.246	0.942	3.202
Loaded C Ni (kg/t)	6.96	7.558	7.382	7.549	3.502	7.189	6.759	6.764	6.48	7.549	5.63	6.735	3.502
Loaded C Cu (kg/t)	0.40	0.462	0.359	0.374	0.894	0.348	0.472	0.369	0.419	0.377	0.416	0.351	3.77
Looded C Ag (kg/t)	1.3	1.4	1.6	1.6	1.8	1.4	1.4	1.5	1.8	1.6	1.1	1.2	1.5
Eluted C Zn (kg/t)	0.12	0.129	0.163	0.141	0.989	0.144	0.116	0.122	0.99	0.125	0.108	0.144	0.116
Eluted C Fe (kg/t)	0.04	0.602	0.446	0.815	0.513	0.556	0.283	0.517	0.241	0.442	0.406	0.556	0.287
Eluted C Ni (kg/t)	5.40	6.37	4.895	6.689	3.068	6.589	7.24	6.746	6.473	6.589	6.71	6.276	6.119
Eluted C Cu (kg/t)	0.1	0.5	0.017	0.377	0.03	0.1	0.3	0.4	0.1	0.3	0.1	0.5	0.3
Eluted Ag Co (kg/t)	0.4	0.8	0.4	0.2	0.5	0.4	0.8	0.1	0.1	0.5	0.4	0.8	0.5
Eluant Zn (kg/t)	0.4	0.3	0.3	0.5	0.8	0.4	0.5	0.8	0.8	0.3	0.4	0.3	0.3
Eluant Fe (mg/l)	1.6	0.8	1.4	1.3	0.1	1.6	2.2	1.6	1.6	1.4	1.6	0.8	1.4
Eluant Ni (mg/l)	400	860	290	380	400	520	290	360	600	520	520	970	690
Eluant Cu (mg/l)	2	0.6	0.6	2.1	2	2.5	2.3	1.6	1.5	2	1.6	1.5	2
EluantAg (g/l)	0.8	0.5	0.5	0.8	0.8	0.8	0.8	1.2	0.4	0.3	1.2	0.4	0.3
Eluant Co (mg/l)	0.7	1.5	0.6	0.8	0.6	0.6	0.8	1.4	1.6	0.7	1.4	1.6	0.7
Eluate Zn (mg/l)	0.4	0.5	0.5	0.2	0.3	0.3	0.5	0.9	1.1	0.5	0.9	1.1	0.5
Eluate Fe (mg/l)	0.1	2.4	1.2	1.6	1.2	0.4	0.2	0.3	0.8	0.3	0.3	0.8	0.3
Eluate Ni (mg/l)	340	950	530	300	380	620	540	530	980	700	530	980	650
Eluate Cu (mg/l)	3.4	1.2	4.2	5.4	4	1.2	3.4	3	1.3	5.4	2.2	0.5	3.1
Eluate Ag (mg/l)	1.7	0.8	1.3	1.4	1.3	1.5	1.8	1.4	1.1	1.5	1.6	1.4	2.9
Eluate Co (mg/l)	0.6	0.6	0.5	0.8	0.7	0.6	0.7	0.7	1.5	0.8	1.4	1.5	0.7
Finesse (%)		85.1		83.27			85.12		82.87			83.24	
Loaded Carbon (g/t)	990	1060	1200	923	958	1030	750	750	1140	980	2050	2050	950
Eluted Carbon (g/t)	180	180	230	190	180	140	80	130	220	170	230	330	150
Elution efficiency (%)	81.8	83.0	80.8	79.4	81.2	86.4	89.3	82.7	80.7	82.7	88.8	83.9	84.2