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Evaluating a Dynamic Model for the Competitive Elution of Gold and Base Metals from Activated Carbon

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ABSTRACT

During the past fifteen years significant progress has been made on carbon-in-pulp (CIP) technology for the extraction of gold. Most research on the mechanisms and kinetics of CIP subprocesses has focused on the adsorption step only; auxiliary unit operations such as elution have received less attention. Mathematical models have been developed for the elution of gold and can be used for design and process optimization. The adverse effect of high loadings of a base metal such as copper on carbon during the desorption of gold is known, but not yet fully understood. A multicomponent Freundlich equilibrium model was used for the simulation and evaluation of the elution of gold and base metals from activated carbon. This model was incorporated in a material balance for a series of well-mixed reactors simulating the effects of an elution column, and was related to the elution of spectator cations such as potassium via an empirical expression. The model successfully simulated the elution profiles, but it was found that base metals, and especially copper(I), complicate the modeling of the base metals due to the consumption of cyanide and the possible formation of polymeric gold-copper species on the carbon surface. The competition coefficients are parameters which indicate the extent to which the base metals affect the elution of gold. At high copper loadings the desorption behavior of copper and gold changed, and an increased adsorptivity was detected. It was postulated that this was mainly due to the formation of copper-gold polymeric chains.

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INTRODUCTION

The carbon-in-pulp (CIP) process is widely used and accepted around the world as a method of extracting gold. During the past years research has helped considerably to understand the different processes in the CIP circuit. It is only recently that some attempts have been made to model the elution step in the CIP process, but most efforts have concentrated on the elution (desorption) of gold only. The effect of base metals such as copper on the elution of gold is well-known in industry, but has not been considered in modeling before. The aim of this paper is therefore to develop and evaluate a dynamic model that will account for the interactive effects of different metal cyanides.

This study is based on the AARL (Anglo American Research Laboratory) elution procedure. In essence, this procedure consists of a presoaking step in the elution column with a caustic cyanide solution, where the aim is to convert any AuCN to $Au(CN)_2^-$ and to decrease the adsorptivity of the activated carbon surface. Subsequently, hot deionized water is used to elute the metal cyanides. A few models have been developed to simulate the elution of gold, most of which were developed for either the Zadra (1) or the AARL (2) elution process. Van der Merwe and Van Deventer (3) proposed a generalized model for simulation of both the Zadra and AARL elution processes which involves the use of a shifting equilibrium isotherm. This is caused by a change in conditions such as the cation and cyanide concentrations. Stange and King (2) and Stange (4) also used the concept of a changing equilibrium isotherm in simulating AARL gold elution profiles.

Van der Merwe and Van Deventer (3) concluded that the mass transfer at industrial elution conditions is very fast and showed that under strong desorption conditions (high temperatures and cyanide pretreatments) the elution of gold is independent of flow rate so that an equilibrium model can be used as a special case of the more complex surface diffusion model. When diffusivities are high, the surface diffusion model will approach the equilibrium model.

EXPERIMENTAL

The experiments were performed using Kopcarb ANK 11 which is a coconut shell activated carbon. Conditioning of the carbon was done by performing an acid wash followed by rinsing the carbon in deionized water. The carbon was loaded with metal cyanides over a period of 48 hours at a pH of 8.5. Carbon with a particle size between 1.4 and 2.36

mm was used and had a pore volume of 8.0×10^{-4} $m^3 \cdot kg^{-1}$ and a bulk density of 490 $kg \cdot m^{-3}$.

The elution studies were conducted at 110°C and a pressure of 200 kPa(gauge). A small stainless column was used with an enclosing jacket. Hot oil was circulated in the jacket, and the temperature was controlled using a feedback controller. The empty volume of the column was 26.5 cm^3 with a height/diameter ratio of 10 and a height of 15 cm. While the column was being heated, the pretreatment was performed using a 20 g KCN/L solution. The AARL elution procedure was used in all the experiments with an eluant flow rate (deionized water) of 3.60 bed volumes/h. The experimental elution profiles are independent of flow rate under strong desorption conditions (5), and therefore a change in flow rate will not affect the simulation results.

The free cyanide concentration in the eluate was determined by $AgNO_3$ titration, where the end point of the reaction was white to yellow and potassium iodide (KI) was used as indicator. The metal and potassium concentrations in solution were determined using an atomic absorption spectrophotometer.

FACTORS AFFECTING THE ELUTION OF METAL CYANIDES

There are various factors affecting the elution of gold cyanide (6), of which cyanide loading (Q_N), temperature (T), pH, and cation (C_K) and cyanide (C_N) concentrations are the most important. The equilibrium can be described by the Freundlich isotherm ($Q = AC^n$) relating the metal loading [Q] to the metal concentration [C] under all process conditions. It was shown by Van der Merwe (5) that the A value can be written as a product of the following functions:

$$A = A_0 \cdot f_1(Q_N) \cdot f_2(C_N) \cdot f_3(\mathrm{pH}) \cdot f_4(C_K) \cdot f_5(T) \quad (1)$$

In the AARL elution procedure the effect of free cyanide carried over from the pretreatment step is of little significance and is therefore not incorporated in the modeling. At a specific elution temperature the pH stays constant. At a constant cyanide loading and temperature these effects can be incorporated into the A_0 value. With pretreatment done at industrial temperatures, the A value can be approximated by

$$A = A_0 \cdot (C_K + 1)^p \quad (2)$$

where p is the dependency of the metal cyanide on the cation concentration. From this it is evident that the AARL gold elution profile is dependent on the removal of the cation, which is potassium in this case. To simulate the Zadra elution procedure, Eq. (2) could be adapted to incorporate factors such as the cyanide concentration and the cyanide loading of the carbon (5). Potassium adsorbs weakly onto the carbon surface, and if not associated with an anion adsorbed as an ion pair on the carbon surface, it is present mainly in the pore liquid of the carbon (7). Electroneutrality is maintained by the presence of cyanide, its degradation products, and hydroxyl ions. Although potassium and cyanide are eluted simultaneously, and earlier than the metal cyanides, the potassium and cyanide profiles are not identical due to the fact that a multitude of anions are associated with the potassium. Only a small fraction of the potassium is associated with the metal cyanides through ion pair formation. The potassium profiles are modeled by a modified nonideal flow model accounting for both macropores and micropores where the pores are represented as two interconnected deadwater regions per section (5). The incorporation of the macropores and micropores enables the modeling of potassium retained through adsorption and that trapped in the pores. Potassium profiles were determined separately for each elution experiment.

All of the above-mentioned factors have an effect on the base metals as well, but they may not be as sensitive to them. For instance, gold cyanide is more sensitive to the removal of the cations than is copper. The base metals are modeled using the same principles that apply to gold cyanide. Modeling the elution of base metals has an added complexity due to the formation of different ratios of metal cyanide complexes, especially with copper. The stability of the different metal cyanide complexes at plant conditions will determine the dominant complexes. In the case of nickel only $Ni(CN)_4^{2-}$ is stable at plant conditions, whereas with copper there exist three different stable cyanide complexes. Copper is mostly adsorbed as $Cu(CN)_2^-$ (8), and with the availability of cyanide via the pretreatment solution, new copper complexes are formed [$Cu(CN)_4^{2-}$ and $Cu(CN)_4^{3-}$]. Their ratios are dependent on the copper-to-cyanide ratio and the pH of the solution. These complexes have different adsorption characteristics due to the difference in anionic charge (9).

MATHEMATICAL MODELING OF COMPETITIVE ELUTION

The ideal adsorbed solution (IAS) theory is used in many cases to predict multicomponent equilibrium data. However, the mathematical and computational effort is substantial and thus limits its applications. However, Fritz et al. (10) stated that the IAS theory does not hold for partially dissociated solutes. Van Deventer (11) showed that the IAS theory is not applicable to metal cyanides. Empirical formulas have been developed to predict multicomponent data like the general multicomponent Freundlich isotherm as derived by Sheindorf et al. (12):

$$Q_i = A_iC_i(\sum_{j=1}^{k} b_{ij}C_j)^{n_i-1} \tag{3}$$

For a single component system ($b_{ij} = 0$), the above equation will simplify to the Freundlich isotherm:

$$Q = AC^n \tag{4}$$

The effect of the different sorbates is introduced by the use of competition coefficients (b_{ij}) and will result in the following for a bicomponent system:

$$Q_1 = A_1C_1(C_1 + b_{12}C_2)^{n_1-1} \tag{5}$$

$$Q_2 = A_2C_2(b_{21}C_1 + C_2)^{n_2-1} \tag{6}$$

The assumption was made that equilibrium exists between the solution and the adsorbent. Van der Merwe and Van Deventer (13) found that the Freundlich-type multicomponent isotherm yielded reasonable approximations of the competitive equilibrium adsorption of gold and silver cyanide. Nieuwoudt (14) also found that Eq. (3) adequately describes the simultaneous adsorption of metal cyanides and, consequently, Eq. (3) was incorporated into the dynamic equilibrium model for competitive elution. Parameter estimation of this multicomponent isotherm is simple compared with that of other isotherms and can be of practical use in industry.

The elution column is modeled as a series of N continuous stirred tank reactors (CSTRs) with a 0th section which represents the inlet concentrations, i.e., the concentrations in the eluant. The column is divided into N sections with height Δh. A mass balance for a single component over the xth section gives (variables refer to the xth section) the following:

$$V(C_{x-1} - C) = a\cdot\Delta h\cdot\rho\cdot(1 - \epsilon)\cdot\frac{dQ}{dt} + \{a\cdot\Delta h\cdot\rho\cdot V_p\cdot(1 - \epsilon) + a\cdot\Delta h\cdot\epsilon\}\frac{dC}{dt} \tag{7}$$

The following symbols are defined for the equations: V is the volumetric flow rate, C is the concentration of the metal cyanide, a is the flow area of the column, ρ is the apparent density of the carbon, Q is the metal loading on the carbon, t is the time variable, ϵ is the void fraction in the carbon bed, and V_p is the specific pore volume of the carbon.

In order to simplify and apply Eq. (7), the time derivative of Eq. (3) must be determined. The result is complicated, because A and n change with time due to equilibrium changes:

$$\frac{dQ_i}{dt} = \frac{dA_i}{dt} C_i s_i^{n_i-1} + \frac{dC_i}{dt} A_i s_i^{n_i-1} + A_i C_i s_i^{n_i-1} \left\{ \frac{dn_i}{dt} \cdot \ln(s_i) \right\} + \tag{8}$$

$$A_i C_i s_i^{n_i-1} \left\{ \frac{(n_i - 1)}{s_i} \left(\frac{dC_i}{dt} + \sum_{j=1,j\neq 1}^{k} b_{ij} \frac{dC_j}{dt} \right) \right\}$$

where

$$s_i = (C_i + \sum_{j=1,j\neq l}^{k} b_{ij} C_j) \tag{9}$$

where i = specific component, $j \neq i$ and k = number of components.

The solution (Eq. 8) can now be substituted back into Eq. (7) which will result in a set of k differential equations with nonlinear terms. These equations must be solved simultaneously by using linear algebra. To use matrices, Eq. (7) must be rewritten in a structured manner which results in the following equations:

$$X_1 = A_i s_i^{n_i-1} + A_i C_i s_i^{n_i-2}(n_i - 1) + z_1 \tag{10}$$

$$X_2 = A_i C_i s_i^{n_i-2} (n_i - 1) \tag{11}$$

$$X_3 = z_2(C_{i,x-1} - C_i) - \frac{dA_i}{dt} C_i s_i^{n_i-1} - A_i C_i s_i^{n_i-1} \frac{dn_i}{dt} \cdot \ln(s) \tag{12}$$

where

$$z_1 = V_p + \frac{\epsilon}{\rho(1 - \epsilon)} \tag{13}$$

$$z_2 = \frac{V}{a \cdot \Delta h \cdot \rho \cdot (1 - \epsilon)} \tag{14}$$

On combining Eqs. (10), (11), and (12), the following matrix equation can be obtained for each component:

$$X_1 \frac{dC_i}{dt} + \sum_{j=1,j\neq i}^{k} (X_2\, b_{ij} \frac{dC_j}{dt}) = X_3 \tag{15}$$

For k components, k matrix equations will be obtained, which can be solved by matrix inversion where the result is a number of simple differential equations. The simple differential equations can be solved using the fourth-order Runge–Kutta method. In each step of the Runge–Kutta method the calculated concentration of each component is substituted back into Eq. (15) which must again be solved by matrix inversion before calculation of the following Runge–Kutta step.

NUMERICAL SOLUTION OF MODEL

It has been shown by Van der Merwe (5) that a linear relationship exists between A and n in Eq. (3) for gold cyanide, and the same linear relationship was assumed for the base metals. From this the following simplifications can be made to Eq. (15) for component i:

$$n = bA + B \tag{16}$$

$$\frac{dn}{dt} = b\frac{dA}{dt} \tag{17}$$

The value of A is dependent on the removal of the cation as indicated by Eq. (2), and therefore at each time step and height increment the A value is known from the potassium profile. Equations (16) and (17) can be used to calculate n and dn/dt. This is done by approximating dA/dt by

$$\frac{dA}{dt} = \frac{A^{t} - A^{t-\Delta t}}{\Delta t} \tag{18}$$

Initial values are needed for the Runge–Kutta method where the initial A value is calculated by the initial concentrations of potassium in the column. Thereafter it is calculated from the values produced by the potassium model which is solved before the equilibrium model at a specific time step. The initial metal loading on the carbon (Q_0) and the initial concentration of the metal cyanide in the pretreatment solution (C_0) are not in equilibrium. From the following mass balance the initial equilibrated concentration of metal cyanide (C_{eq}) can be approximated:

$$AC_{eq}^{n} + z_1C_{eq} = Q_0 + (z_1 - V_p)C_0 + V_pC_{p0} \tag{19}$$

The initial concentration is approximated by a single component isotherm instead of the multicomponent isotherm, due to the fact that the multicomponent isotherm will result in a set of complex equations which will make its simultaneous solution difficult.

With all the initial conditions known, the model can be solved starting at the bottom of the column and sequentially stepping through the sections using the results of the previous section and ending at the top (section N). The equilibrium multicomponent equations for each section are solved by matrix inversion and the differential equations by the Runge–Kutta method. The time is increased by Δt (time step), and the model is solved again starting from the bottom of the column. This procedure is followed until the desired time has been reached using sequential time steps.

RESULTS

It is well-known that some base metals such as copper have a detrimental effect on the elution of gold. The multicomponent model was used to simulate the effect of different copper loadings on the elution of gold during an AARL elution.

The experimental data and model simulations are illustrated in Figs. 1–3. In the simulations, $N = 5$ was used, which indicates some backmixing and channeling in the column. Model parameters were kept constant for the simulations and were determined by fitting the model to experimental data. The model parameters are stated in Table 1. The simulated gold and copper elution profiles were modeled using the same competition coefficients for all three simulations, i.e., the value of 0.02 for copper on gold ($b_{\mathrm{Au,Cu}}$) and 0.2 for gold on copper ($b_{\mathrm{Cu,Au}}$). The following relationship between n and A was used in the simulations for gold and copper:

$$\text{Au:} \quad n = -0.0052 \cdot A + 0.34 \tag{20}$$

$$\text{Cu:} \quad n = -0.0075 \cdot A + 0.46 \tag{21}$$

The data in Table 1 show a decline in the elution efficiency of the gold with an increase in the copper loading. This tendency is well known in industry. It is often believed that with an increase in the copper loading, the cyanide available in the pretreatment step for the elution of gold de-

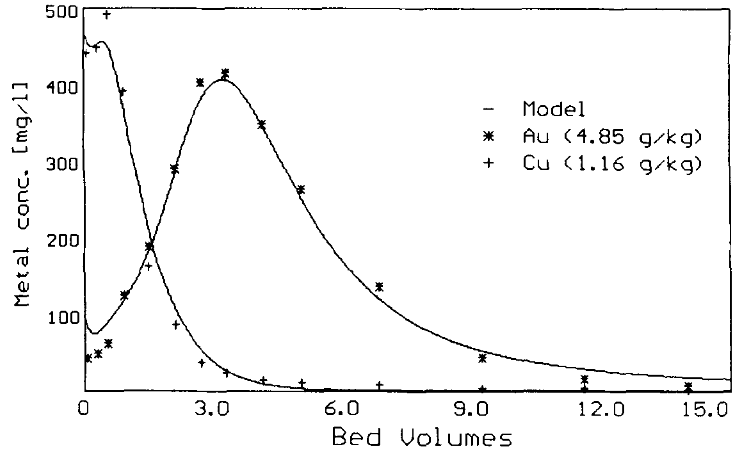

FIG. 1 Simulation of gold and copper elution profiles at low copper loadings.

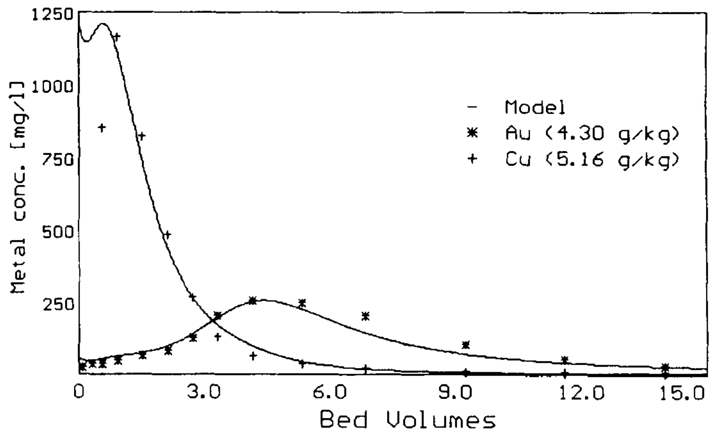

FIG. 2 Simulation of gold and copper elution profiles at medium copper loadings.

creases. The same pretreatment was performed, and it can be reasoned that due to the limited amount of cyanide available, the ratio of Cu(CN)$_3^{2-}$ to Cu(CN)$_4^{3-}$ will increase with an increase in the copper loading, which will lead to a lower free cyanide concentration in solution. The cyanide levels were monitored and, as illustrated in Fig. 4, there was an excess of cyanide with no significant decrease in cyanide levels with an increase in copper loading. It is thus possible that the decrease in gold recovery may be due to increased copper–gold surface interactions at higher copper loadings and not to the cyanide deficiency.

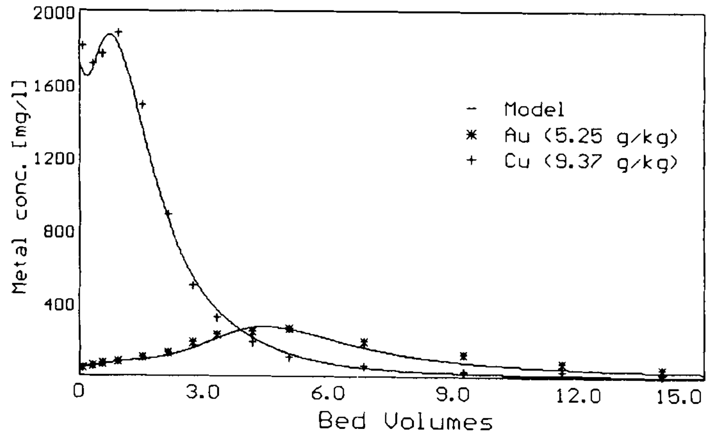

FIG. 3 Simulation of gold and copper elution profiles at high copper loadings.

TABLE 1
Parameters Used in Model Predictions

	Figure no.		
	1	2	3
Au:			
Q_0 (g/kg)	4.85	4.30	5.25
p	0.32	0.32	0.32
A_0	0.079	0.096	0.104
Recovery (%)	86	79	75
Cu:			
Q_0 (g/kg)	1.16	5.16	9.37
p	0.19	0.19	0.19
A_0	0.01	0.027	0.044
Recovery (%)	100	100	100

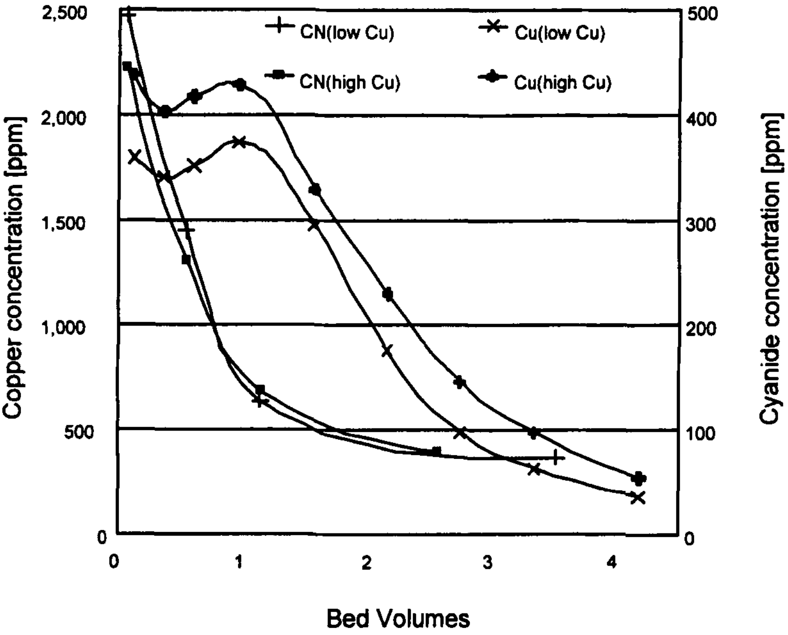

FIG. 4 Copper (Cu) and cyanide (CN) elution profiles with (low Cu) = 9.37 g Cu/kg and (high Cu) = 14.61 g Cu/kg.

There is an increase in the A_0 value of copper and gold with an increase in the copper loading (Table 1). This phenomenon can be explained by two mechanisms, i.e., first, most of the free cyanide is eluted before the copper, and the absence of high levels of free cyanide leads to the formation of the $Cu(CN)_3^{2-}$ complex rather than the $Cu(CN)_4^{3-}$ complex, with $Cu(CN)_3^{2-}$ having a higher adsorption affinity than $Cu(CN)_4^{3-}$. Second, copper-gold compounds or polymeric chains may form at high copper loadings. This will lead to higher adsorption levels and an increase in the A_0 value. De Kock and Van Deventer (15) proposed the formation of a copper-gold surface compound at high copper loadings to explain the sorption equilibria where copper and gold are involved. The surface compound had higher adsorption characteristics than either the copper or the gold.

Kongolo et al. (16) investigated the formation of different gold species by Mössbauer studies and concluded that under conditions of low pH and high temperature, polymeric —CN—Au—CN—Au—CN– chains are formed. Under acid wash conditions these chains can form at adsorption sites with lower binding energies. The possibility exists that —CN—Au—CN—Cu—CN— chains can form if the species were loaded at adjacent sites. These formations will vary from site to site and will depend on the adsorption energy of the site. It is known that copper(I) has a catalyzing effect on the oxidation of cyanide (17), and there exists the possibility that copper can have an influence on the stability of the $Au(CN)_2^-$ complex. However, the results indicate that both copper and gold complexes have undergone changes on the carbon surface. These changes lead to the formation of irreversibly adsorbed species.

EVALUATION OF MODEL

From the mass balance (Eq. 19) the equilibrated initial concentration is calculated where the initial pore concentration (C_{p0}) as well as C_0 are normally zero (no metal cyanides present in pretreatment reagent) and results in the following equation:

$$AC_{eq}^n + z_1C_{eq} = Q_0 \tag{22}$$

Equation (22) is solved by using the single component Freundlich isotherm (Eq. 4) and not the multicomponent isotherm, due to the fact that this will complicate the simultaneous solution of the resulting set of equations. Approximating the initial values by the multicomponent isotherm will lead to higher initial gold values in solution due to the competitive effect with $b_{Au,Cu} = 0.02$.

A higher concentration of the competitive metal (C_{Cu}) will lead to a lower loading of gold (Q_{Au}) due to the competitive effect described by the multicomponent isotherm. Theoretically (and mathematically), when desorption is predicted by the multicomponent isotherm and there is a high C_{Cu} in solution, there should be a higher concentration of gold in solution than would be the case in a single solute system to predict the same loading. This means that copper in solution enhances the elution of the gold, which is not the case due to chemical changes during the pretreatment step. When looking at the experimental initial values of gold in solution at different copper loadings (Fig. 5), it is clear that a higher copper loading (and subsequently higher equilibrated initial copper values) leads to a lower initial gold value in solution, which is in contradiction to what could be expected from the multicomponent isotherm prediction. The relative initial gold desorption in Fig. 5 was determined by dividing the initial gold concentration in solution by the initial gold loading on the carbon. If copper in solution does enhance the elution of gold, it is relatively unimportant compared to other factors such as the cation concentration, concentration of the pretreatment reagent, and the chemical changes that take place on the carbon surface during pretreatment.

From the above explanation it is evident that the initial metal concentrations calculated with the single component isotherm are closer to the experimental value than those calculated with the multicomponent isotherm. Although the multicomponent isotherm was used in the modeling of the elution profiles, the single component isotherm was used for calculating the initial values. This will lead to a lower effective gold loading. This effect is simulated in Table 2 where the single component determined initial equilibrated gold concentration (43 mg/L) is used in the single and multicomponent equilibrium isotherms to predict the loading. The multi-

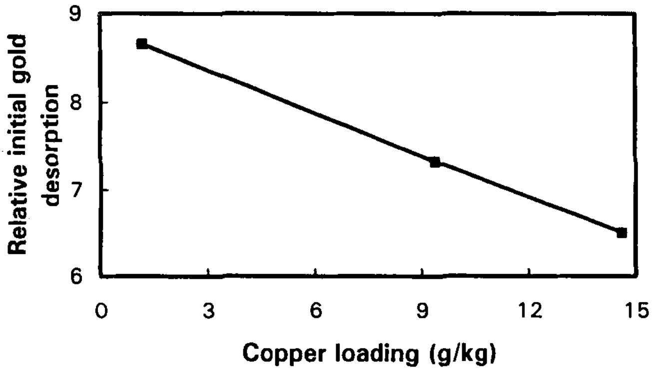

FIG. 5 Relative experimental initial gold desorption vs the copper loading on the carbon.

TABLE 2
Prediction of Initial Conditions

$C_{Cu.eq}$	C_K	$C_{Au.eq}$	*A* value	$Q_{eq.Au}$	$Q_{0.Au}$ (predicted)	Comp. coef. (b_{ij})
1720	4000	43	1.48	5.18	5.25	0 (single)
1720	4000	43	1.48	3.50	3.57	0.02 (multi)
1720	4000	83	1.48	5.11	5.25	0.02 (multi)

component predicted equilibrium loading is lower (3.50 g/kg) than that predicted with the single component isotherm (5.18 g/kg). The multicomponent isotherm simplifies to the single component Freundlich isotherm when the competition coefficient is zero. Thus, by using initial values predicted by the single component isotherm and using the multicomponent isotherm for further elution predictions, the effective loading is lowered.

The values in Table 2 were taken from the experimental values of Fig. 3 where the $Q_{0,Au}$ = 5.25 g/kg. For the $Q_{0,Au}$ to be 5.25 g/kg in the equilibrated solution with b_{ij} = 0.02, the initial gold concentration in solution must be 83 mg/L. In using the value predicted by the single component isotherm (43 mg/L), the effective loading is lowered by the competition coefficient. The difference between the experimental values and the single component predicted values was small enough to simulate the elution profiles successfully. This strategy approximates a gradual shift in the competition coefficient from zero or perhaps negative values to positive values as copper is eluted.

The complexity of the chemical changes that take place during the pretreatment step was thus successfully modeled by mathematical manipulation, but emphasizes the poor understanding of the interactions between the species. In this case the competition coefficient is rather a parameter indicating the extent to which copper influences the recovery of gold. The higher the competition coefficient the stronger the detrimental effect of the base metal on the recovery of gold. It is clear that the metal cyanide interactions during the elution procedure are of minor importance compared with the chemical changes that take place during the pretreatment stage. Although a fundamental approach was followed, the result was a semiempirical model for the prediction of competitive elution.

SENSITIVITY ANALYSIS

The effect of some of the operating parameters on the elution profiles has been studied by Van der Merwe (5), but only for a single component

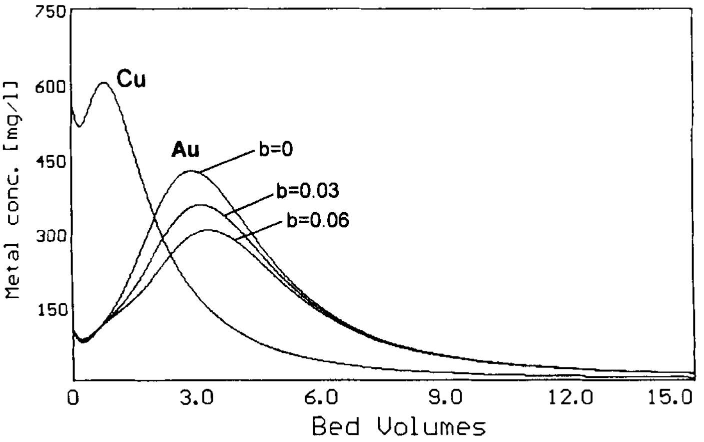

FIG. 6 Prediction of the effect of competition coefficients ($b_{Au,Cu}$) of Cu and Au on elution profiles.

system. The incorporation of the multicomponent isotherm and subsequently the competition coefficients results in additional variables for the system which makes the simulations more difficult due to the interaction between metal cyanides. The effect of the competition coefficients ($b_{Au,Cu}$) of copper on gold on the elution profile of gold is illustrated in Fig. 6 with the modeling parameters given in Table 3. From the simulations it is evident that the competition coefficient is a parameter that indicates the degree to which the base metal influences the gold recovery. The competition coefficients will change with a change in pretreatment conditions such as cyanide concentration and pretreatment temperature.

The elution of gold and the base metals is dependent on the removal of the cations present. In this case most of the cations (potassium) and cyanide are eluted simultaneously and before any appreciable gold elution. The dependency of the metal is indicated by parameter p in Eq. (2), and experimental data have shown that gold is more sensitive to the removal of cations than is copper. The cation inhibits the elution of metal cyanides

TABLE 3
Parameters for Model Prediction in Fig. 6

	Au	Cu
Q_0 (g/kg)	4.5	3.5
A_0	0.07	0.06
p	0.32	0.2

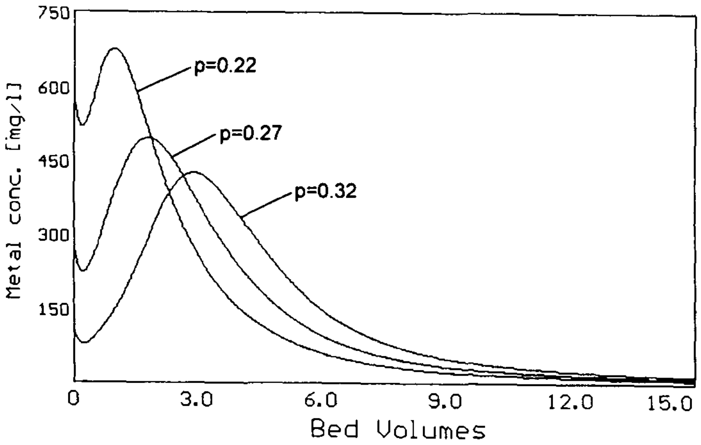

FIG. 7 Prediction of effect of cation dependency (p) on elution profile.

that adsorb stronger onto carbon. This is due to the formation of neutral ion-pairs ($K^+Au(CN)_2^-$) on the negatively charged carbon surface where the high concentration of potassium ions inhibits the elution of gold. Desorption would only be favored once the concentration of the cations is lowered, and the effect of the negative charge density increases on the ion-pairs. The cation dependency (p) is determined by fitting the model to experimental data. The effect of the cation dependency (p) on the elution profiles is illustrated in Fig. 7 with an initial metal loading of 4.0 g/kg and an A_0 value of 0.07.

CONCLUSIONS

It was shown that a multicomponent isotherm can be introduced into the equilibrium elution model. The model satisfactorily predicted the elution profiles in a binary system of copper and gold. Competition coefficients in a multicomponent model can be used to simulate the effect of base metals on the elution of gold and indicates the degree to which the base metals affect the recovery of gold. The competition coefficients must be regarded as an empirical fitting, so that assumptions made in the original derivation of the multicomponent equilibrium isotherm may not hold. In a real system it may be necessary to lump together more than one competitive species.

Chemical changes on the carbon surface and changes to the different adsorbed metal cyanide complexes during pretreatment may shed some light on the suspected interactions of the species and aid in the formulation of a more fundamental model. Factors such as the cyanide concentration, pH, pretreatment temperature, and base metal loading will determine the structure of the metal cyanide or combinations of different metal cyanides on the carbon surface. The identification of the surface-loaded species will greatly aid in the understanding of the effect of base metals on gold sorption. The experimental results support the theory that at high copper loadings a fraction of the gold and copper forms copper-gold surface compounds, and it is further postulated that these species might be polymeric chains on the carbon surface. Further research is required to quantify the interactions of the different metal cyanides and the existence of the postulated polymeric chains.

SYMBOLS

A	parameter in Freundlich and isotherm
A_0	constant in Freundlich isotherm
a	flow area of column (m^2)
b	constant in isotherm expression, Eq. (16)
b_{ij}	competition coefficient
B	constant in isotherm expression, Eq. (16)
C	liquid phase concentration ($g \cdot m^{-3}$)
h	column height (m)
k	number of components present
N	number of height sections in column
n	exponent in Freundlich isotherm
p	parameter describing the effect of potassium on the equilibrium
Q	concentration of adsorbent on carbon surface ($g \cdot kg^{-1}$)
s_i	parameter as described in Eq. (9)
T	temperature (K)
t	time variable (s)
Δt	value of time increment
V	flow rate ($m^3 \cdot s^{-1}$)
V_p	specific pore volume ($m^3 \cdot kg^{-1}$)
X_1, X_2, X_3	parameters as described in Eqs. (10), (11), and (12)
z_1, z_2	constants in Eqs. (13) and (14)

Greek Symbols

ϵ	void fraction in carbon bed
ρ	apparent density of carbon ($kg \cdot m^{-3}$)
Δ	increment

Subscripts

Au	gold
eq	equilibrated
Cu	copper
i	refers to specific metal cyanide sorbate
j	refers to competing metal cyanide sorbate (running variable)
K	potassium
N	cyanide
0	initial value
p	pore
x	index referring to section x of the column

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