

A mathematical model of the leaching of gold in cyanide solutions

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Received 25 August 1995; accepted 13 April 1996

Abstract

The chemistry of the dissolution of gold in cyanide solutions has received considerable attention. However, few rate expressions which describe the leaching of gold ores have been developed. A model, based on the shrinking-particle model, is presented here. In this work, it is proposed that a layer of passivating material forms on the surface of the gold particle as it dissolves. As the total surface area diminishes in size, the passivating layer grows to increase its coverage of the surface. The formation of the passive layer has little influence on the reaction in the initial stages of the batch experiment; however, in the latter stages it has a dominant influence. In this work it is proposed that the dissolution reaction is described by a mixed-potential model in which the reaction at the surface is rate controlling. Experiments were conducted in which both the concentration of oxygen and cyanide were maintained at a fixed value throughout the batch experiment. The concentration of cyanide was controlled by a computer operated system which uses an amperometric measurement of the concentration of cyanide. It is shown that the mathematical model of the leaching reactions is an excellent description of the measured data reported here. The rate constant for the dissolution reaction is shown to be dependent on the square root of the concentration of cyanide, which is in agreement with the proposed mixed-potential model. The results presented here contrast strongly with the previously accepted model of the dissolution reaction, which is based on the diffusion of either cyanide or oxygen. This previous model predicts a first-order dependence on the concentration of cyanide in solution, which clearly contrasts with the results presented here.

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1. Introduction

Since the late 19th century, when cyanidation was introduced as an industrial process for the extraction of gold [1], the chemistry of the dissolution of gold in alkaline cyanide solutions has been the subject of considerable investigation [2]. Early studies established the stoichiometry and the thermodynamics of the reaction, and investigated the effects of the concentration of cyanide and oxygen on the rate of reaction. However, many of these studies were contradictory in their conclusions concerning the mechanism of dissolution, with some claiming that the diffusion of reactants to the gold surface controls the rate of reaction, while others claimed that the chemical reaction is slow [2].

A significant step in the understanding of gold dissolution was made by Kudryk and Kellogg [3], who demonstrated that the reaction is an electrochemical corrosion process. They determined the anodic and cathodic polarisation curves, and used these curves to determine the effects of the concentration of oxygen and cyanide on the rate of reaction. They concluded that the rate is determined by the diffusion of either oxygen or cyanide to the gold surface, depending on the relative concentrations of oxygen and cyanide in the solution.

A number of studies of the anodic dissolution of gold have been published since the work of Kudryk and Kellogg [3]. These studies have been reviewed by Nicol [4]. In contrast to the results of Kudryk and Kellogg [3], whose anodic polarisation curve is described by mixed reaction–diffusion control, most subsequent studies have identified the formation of different passivating films on the surface of the gold electrode. These passivating films are associated with anodic peaks that occur at potentials of about -0.4 V, 0.3 V and 0.6 V (vs. normal hydrogen electrode). The peaks at 0.3 and 0.6 V are associated with the formation of oxide films, and Cathro and Koch [5] have argued that passivation in the region of the peak at -0.4 V is associated with the formation of a monolayer of AuCN adsorbed on the surface. During cyanidation, the potential of the gold remains at values less than zero, that is, within the region of this peak at -0.4 V.

Mills [6] and Cathro [7] demonstrated that the presence of very low concentrations of heavy metal ions, such as those of lead, mercury, bismuth and thallium, can have a significant effect on the extent of passivation; indeed, passivation does not occur in the region of this peak in the presence of thallium. On the other hand, Fink and Putnam [8] demonstrated that sulphide ions inhibit the rate of dissolution.

The cathodic reduction of oxygen in alkaline solutions at a gold electrode proceeds via a mechanism in which the formation of HO_2^- (ads), a surface intermediate in the reaction, is the rate-controlling step [9–11]. However, it is still uncertain whether the reduction of oxygen terminates with the formation of hydrogen peroxide, or at hydroxide [12]. It has been reported that the rate of reduction of oxygen may be slower in the presence of cyanide than in its absence [13].

In contrast with the large number of investigations of the chemistry of the dissolution of gold, not many studies of the leaching of gold ores have been reported, and even fewer rate expressions describing the leaching of ores have been developed.

Brittan [14] argued that kinetic treatments of leaching are too limited to describe leaching reactions involving low-grade ores, and that rigorous representation of all the rate-controlling factors in real ores would be impractical. He therefore proposed a

variable activation energy model in which all the rate-limiting effects are lumped together as an Arrhenius energy barrier. As the reaction proceeds, the more reactive material dissolves first, leaving material that is less reactive. This is described by increasing the activation energy during the course of the reaction. His expression for gold leaching is:

$$-\frac{d[\text{Au}]}{dt} = ([\text{Au}] - [\text{Au}]^*) \exp\{b_1([\text{Au}] - [\text{Au}]^*) - b_2\} \quad (1)$$

where $[\text{Au}]$ represents the concentration of undissolved gold (remaining in the ore); $[\text{Au}]^*$ represents the concentration of refractory gold, which is unliberated and therefore insoluble in cyanide solutions; b_1 and b_2 are constants. Brittan [14] reported good fits of his rate expression with the data of the leaching of some typical gold ores.

Nicol et al. [15] developed an expression for the leaching of gold as part of a programme to model the multistage adsorption circuits in the carbon-in-pulp and carbon-in-leach processes. They proposed an empirical equation, derived from leaching experience with South African ores, of the following form:

$$-\frac{d[\text{Au}]}{dt} = k_p([\text{Au}] - [\text{Au}]^*)^2 \quad (2)$$

They reported good agreement for the fit of this expression with the data for the leaching of a high-grade ore and a low-grade residue. They noted that the rate constant k_p varied in the limited range of 0.4–1.0 h^{-1} for the data of 6 different ores. They suggested that an average value of 0.7 h^{-1} would be a reasonable estimate for an untested ore.

McLaughlin and Agar [16] developed a similar model to that of Nicol et al. [15]. Where Nicol et al. [15] proposed a model that is second order in the amount of unreacted gold, McLaughlin and Agar [16] proposed a first-order model. This model is given by:

$$-\frac{d[\text{Au}]}{dt} = k_p([\text{Au}] - [\text{Au}]^*) \quad (3)$$

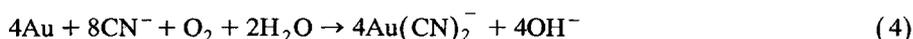
All the leaching models that have been proposed previously lump a number of effects together. They do not attempt to describe the processes that occur during particulate leaching. All these expressions are those of homogeneous kinetics. Leaching is a heterogeneous reaction which includes a diminishing surface area as the reaction proceeds.

Experimental work that has been reported previously has determined the extent of the leaching reaction in either open agitated tanks or in rolling bottles. In both these types of experiments, there are at least two reasons that there may be significant loss of cyanide during the course of the experiment. Firstly, the concentration of cyanide may be depleted as a result of material in the ore, such as soluble iron oxides or sulphides, that consume cyanide. Secondly, in experiments conducted in open tanks, there may be a significant loss of cyanide to the atmosphere as a result of the hydrolysis of cyanide to hydrogen cyanide and the stripping of the hydrogen cyanide by the gas that is sparged into the slurry. It is essential to be able to control the concentrations of cyanide and oxygen during the course of the experiment in order to obtain reliable experimental data.

It is apparent that, while a considerable amount of investigation has concerned the chemistry of gold dissolution, very little attention has been paid to the kinetics of the leaching of gold ores. The aim of this paper is to present experimental results and a mathematical model for the leaching of gold. These experimental results were obtained under conditions in which the concentration of cyanide was controlled throughout the course of the reaction. The mathematical model is based on the chemistry of gold dissolution and on the shrinking-particle model for the leaching of particulate material.

2. Mathematical model of gold leaching

The leaching of gold from an ore can be described by the following reaction:



Since the rate of this reaction is dependent on the available surface, the mass balance for the leaching of gold in a batch reactor is given by:

$$\frac{dN_{\text{Au}}}{dt} = -r_{\text{Au}}A \quad (5)$$

where N_{Au} represents the number of moles of solid (particulate) gold in the batch reactor, r_{Au} represents the rate of consumption of gold by the leaching reaction (units of mol/m²s), and A represents the available surface area (m²).

In order to derive a mathematical model for the leaching of gold from Eq. (5), expressions for the rate of reaction, r_{Au} , and for the available surface area, A , are required. In this study, these two expressions are derived from the electrochemical mechanism of gold leaching and from the shrinking-particle model with surface passivation. Neither mechanism has been presented before by researchers; they are discussed in detail in the next two sections.

2.1. Electrochemical mechanism of leaching of gold

The dissolution of the gold occurs in the following steps: (1) diffusion of the reactants in solution through a liquid film to the unreacted gold surface; (2) chemical reaction of the reactants in solution with the metallic gold; and (3) diffusion of products through a film boundary layer away from the surface. The rate of reaction, r_{Au} , is dependent on which of these steps, or combination of steps, is rate controlling.

It is generally accepted that the dissolution of gold by oxygen in cyanide solutions is an electrochemical process. The anodic half-reaction for gold leaching is given by:



and the cathodic half-reaction is given by:



Data for the anodic dissolution of gold in the region of the current peak at -0.4 V vs. NHE indicates that the anodic current density is dependent on the concentration of

cyanide and has a Tafel slope of 120 mV/decade [5,17,18]. The order of reaction has been reported as 1, 1.27 and 1.5. Assuming that the reaction order is 1, then the anodic current density, i_a , is given by:

$$i_a = k_a[\text{CN}^-] \exp(\alpha_a E_H F/RT) \quad (8)$$

where α_a , the charge-transfer coefficient, has a value of 0.5; E_H is the potential difference across the metal–solution phase boundary (relative to a common reference electrode); R is the gas constant; T is the temperature, and k_a is a rate constant.

Zurilla et al. [11] have shown that the current density due to the reduction of oxygen at a gold electrode is first order in the concentration of oxygen and has a Tafel slope of 120 mV/decade. This is given by:

$$i_c = k_c[\text{O}_2] \exp\{-(1 - \alpha_c)E_H F/RT\} \quad (9)$$

where the value of α_c is 0.5.

Eq. (8) and Eq. (9) represent the rate of the production and consumption of electrons in the two half reactions of gold leaching. Since there is no accumulation of charge during leaching, these rates are equal; that is:

$$i_a = i_c \quad (10)$$

By substituting Eq. (8) and Eq. (9) into Eq. (10), we obtain an expression for the mixed potential of the gold surface during leaching. This is given by:

$$E_H = \frac{RT}{F} \ln \left(\frac{k_c[\text{O}_2]}{k_a[\text{CN}^-]} \right) \quad (11)$$

By substituting this expression for the mixed potential into Eq. (8), we find that the current density for the anodic half-reaction is given by:

$$i_a = (k_a[\text{CN}^-])^{0.5} (k_c[\text{O}_2])^{0.5} \quad (12)$$

The current density for the anodic half-reaction is related to the rate of consumption of cyanide, r_{Au} , by Faraday's law:

$$r_{\text{Au}} = \frac{i_a}{F} = \frac{1}{F} (k_a[\text{CN}^-])^{0.5} (k_c[\text{O}_2])^{0.5} \quad (13)$$

This equation describes the rate of leaching. It is one-half order in the concentrations of cyanide and oxygen. In the derivation of this rate expression, it was assumed that the rate of the anodic and cathodic half-reactions were controlled by the rate of electrochemical reaction, and not by the diffusion processes mentioned at the beginning of this section. It is possible to extend this derivation to account for these transport steps if necessary.

2.2. Passivation of the gold surface during leaching

The passivation of the gold surface, either by reaction products such as AuCN or by poisons such as sulphide ions has been mentioned. For example, the anodic dissolution

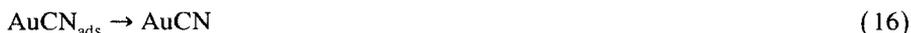
reaction is thought to occur in two steps. The first step is the formation of the adsorbed intermediate, AuCN_{ads} , by the reaction:



and the second step is the dissolution of the adsorbed intermediate by the reaction:



The AuCN_{ads} intermediate may, however, crystallise to form an AuCN precipitate, or a passivating layer. This is represented by the reaction:



If the AuCN prevents further reaction at that point and the coverage of the surface by the AuCN becomes significant, then it is necessary to account for this in the shrinking-particle model. There are other ions in solution that have been implicated in the passivation of the gold surface. For this treatment, it is not necessary that the nature of the passivating film is identified.

Consider a passivating film that grows at a rate proportional to the amount of surface area that is not covered by the film and that dissolves at a rate proportional to the amount of surface area that is covered by the film. If f represents the fraction of the total surface area that is covered by passivating film and A represents the total surface area, then a mass balance for the film on the gold surface gives:

$$\frac{dfA}{dt} = k_2(1-f)A - k_{-2}fA \quad (17)$$

where k_2 and k_{-2} are rate constants. It is assumed that there is no passivating film present on the gold surface at the beginning of the leaching process (i.e., $f = 0$ at $t = 0$).

2.3. Shrinking-particle model with electrochemical reaction and surface passivation

The mineralogy of the gold in milled ores is not easily observed. The ore consists mainly of ground silica particles and the concentration of gold is low. In such ores, most of the soluble gold occurs as fully liberated gold particles [19]. We propose that the particles of gold can be represented as fully liberated particles of regular shape and uniform size. The assumption of regular shape is often made in solid–fluid reactions. It is easily shown that the shrinking-particle model for regular particles which maintain their initial aspect ratio during the course of the reaction are described by the same equation as that for spherical particles. For this reason, we will treat the particles as spheres. The assumption of a uniform size distribution is made because accurate data is unavailable. Measurements of the size distribution of the gold particles in a milled ore are very difficult and are therefore rare [20]. Those distributions that have been reported are uninodal, and have a smaller mean and variance than the milled ore [20]. Unless the size distribution has more than one node (maximum), it can be shown that the size distribution cannot account for the dissolution curves reported here.

The dissolution of gold can only occur on a surface that is not covered by the

passivating film. Therefore, the mass balance for the batch reactor, given by Eq. (5), becomes:

$$\frac{dN_{Au}}{dt} = -r_{Au}(1-f)A \quad (18)$$

The change in the number of moles of solid (particulate) gold is related to the change in size of the gold particle. For spherical gold particles with radius r , we obtain that the relationships [25]:

$$dN_{Au} = 4\pi r^2 \rho_{Au} dr \quad (19)$$

$$A = 4\pi r^2 \quad (20)$$

and:

$$X = 1 - \left(\frac{r}{R}\right)^3 \quad (21)$$

where ρ_{Au} is the molar density of gold, X is the reaction conversion, and R is the initial particle size.

Substituting these relationships and Eq. (13) into the mass balance, Eq. (18), and after some rearrangement, the leaching of gold in a batch reactor is described by:

$$\frac{dX}{dt} = k_s(1-X)^{2/3}(1-f) \quad (22)$$

where $k_s = 3(k_a k_c [CN^-][O_2])^{0.5} / \rho_{Au} RF$. The initial condition is $X = 0$ at $t = 0$.

Substituting Eq. (20) and Eq. (21) into Eq. (17), we obtain the following expression describing the fraction of surface that is covered by passivating film:

$$\frac{df}{dt} = k_2(1-f) - k_{-2}f + \frac{2}{3}k_s f(1-f)(1-X)^{-1/3} \quad (23)$$

The initial condition is $f = 0$ at $t = 0$.

Therefore, the dissolution of gold is described by the simultaneous solution of Eq. (22) and Eq. (23).

3. Experimental

3.1. Apparatus and materials

Two samples of milled gold ore from a mine on the Witwatersrand Reef (West Rand) were obtained. These samples were taken from the feed to the leaching plant, and copper sulphate was immediately added to the sample to consume any free cyanide that may have been present in the solution. The sample was washed with water, filtered, dried and blended in the laboratory. The head grade for both these ore samples was 15.6 mg/kg.

Leaching experiments were performed in a 15 l baffled vessel. The vessel was agitated by a flat blade impeller driven by an overhead motor at a rotation speed of 200 min^{-1} . The vessel was covered by a lid which had ports for an air sparger, a

thermometer, a custom-made cyanide probe, and for cyanide addition and sampling. The leaching vessel was placed in a constant temperature bath in order to maintain the temperature at 21°C. Air was sparged into the vessel. The supply of air was sufficient to maintain the concentration at the saturation level (7.1 g/m³). The concentration of oxygen was measured regularly throughout each experiment.

The concentration of cyanide in the vessel was controlled by a computer-controlled feedback system. The cyanide in solution in the vessel was measured by an amperometric technique described in [21,22]. The technique is based on the measurement of the current due to the anodic dissolution of a copper electrode at a controlled potential. The potential of the copper anode was controlled by a BAS CV 27 potentiostat. The current, which is directly proportional to the concentration of free cyanide in solution, was measured by a Hewlett Packard data acquisition system and computer. A computer program implemented the PID control. The computer and acquisition system signalled whether a control valve should open or close. This valve controlled the addition of a concentrated solution of sodium cyanide to the tank in order to maintain the concentration of cyanide in solution at its initial value. A schematic diagram of the apparatus and the control system is shown in Fig. 1.

The slurry samples were filtered through a Millipore membrane (0.2 μm) under pressure. The concentration of cyanide in solution was checked by titration with silver

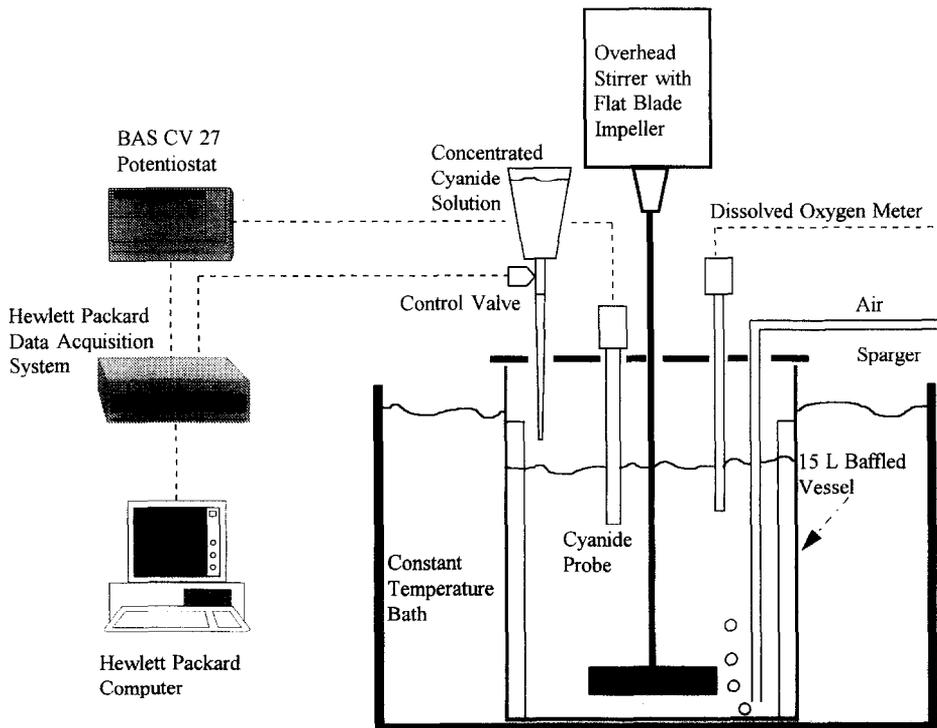


Fig. 1. Schematic diagram of the leaching apparatus and the cyanide control system.

nitrate, and the concentration of gold was determined by a Varian atomic absorption spectrophotometer (AA).

3.2. Procedure

A slurry was made from 6 kg of dry ore sample and 6 kg of water. Boric acid (5 g/l) was added as a pH buffer, and the pH was adjusted to 10.3 by adding sodium hydroxide. Air was sparged into the vessel for about 10 min to ensure that the solution was saturated with oxygen. This was verified by measuring the concentration of oxygen. A measured amount of sodium cyanide was added to the solution to begin the reaction and the cyanide control system was switched on. The control system maintained the cyanide concentration at its initial value for the duration of the experiment. Samples were withdrawn from the vessel and immediately filtered. The concentration of gold in the solution was determined by AA.

4. Results and discussion

The results for the dissolution of gold in large scale vessels for two different ores are shown in Fig. 2. The first ore is a primary source from a high-grade Witwatersrand gold

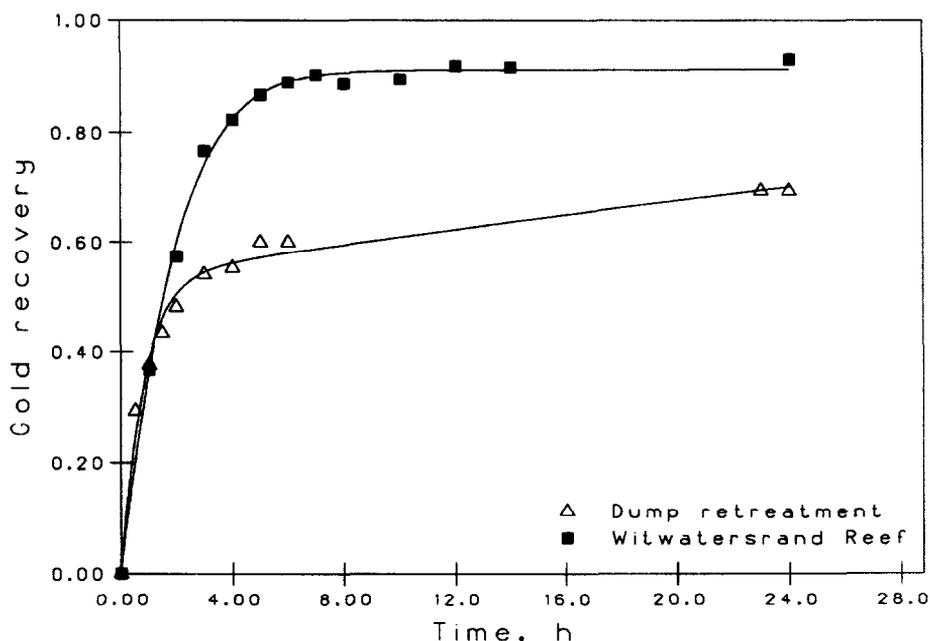


Fig. 2. Plant tests for the leaching of gold in cyanide solutions in full-scale tanks. The data are for two different ore sources: a primary Witwatersrand ore, and a secondary dump ore. The primary ore is relatively high-grade material, while the secondary ore is low-grade material. The lines represent the fit of the mathematical model, given by Eqs. (22) and (23), to the data.

mine, while the second ore is a secondary source from a low-grade dump retreatment operation close to Johannesburg. The rate of leaching is typically large during the initial period, which in these results is up to about 6 h. After the initial period the rate of leaching diminishes considerably, but may not be zero. This is most clearly illustrated in the results for the leaching of the material from the dump retreatment process. Although the rate of leaching is low, a significant amount of leaching occurs between 4 and 24 h.

These results illustrate that it is often difficult to determine the amount of leachable gold. The head grade determines the total amount of gold in the ore, but there may be a significant amount of gold that is not exposed to the leaching solution and, even if the gold is exposed to the solution, the rate of leaching is slow but finite for an extended period. In addition, the final recovery after a fixed period, say 24 h, is often dependent on the concentration of cyanide and oxygen. This is true for the results presented in this paper for South African ores, and for the results presented by McLaughlin and Agar [16] for a Canadian ore.

A successful mathematical model of the leaching of gold must describe the two distinct regions of the reaction curve; that is, the fast reaction region that occurs in the initial stages, and the slower reaction region in the latter stages. The lines in Fig. 2 represent the mathematical model. These results indicate that the model is a good description of the leaching curve. The change in rate of reaction is accounted for by the shrinkage of the gold particle and by the growth of a layer of passivating material on the surface of the gold. In the initial stages of the reaction the surface is free of the

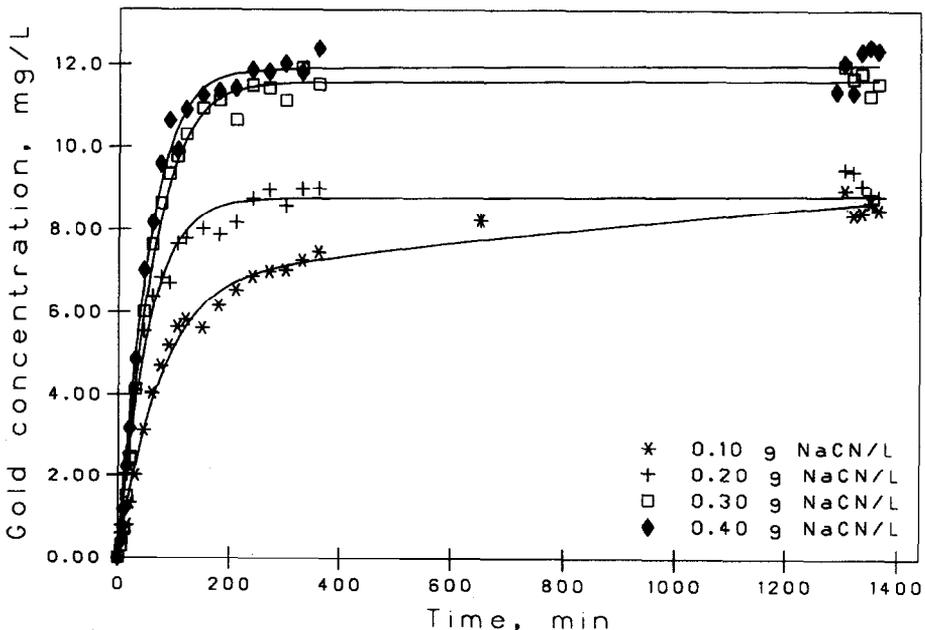


Fig. 3. The leaching of gold from ore sample 1 for different cyanide concentrations. The points represent the data, while the lines represent the fit of the mathematical model Eqs. (22) and (23) to the data. The parameters obtained from fitting the model to the data are presented in Table 1.

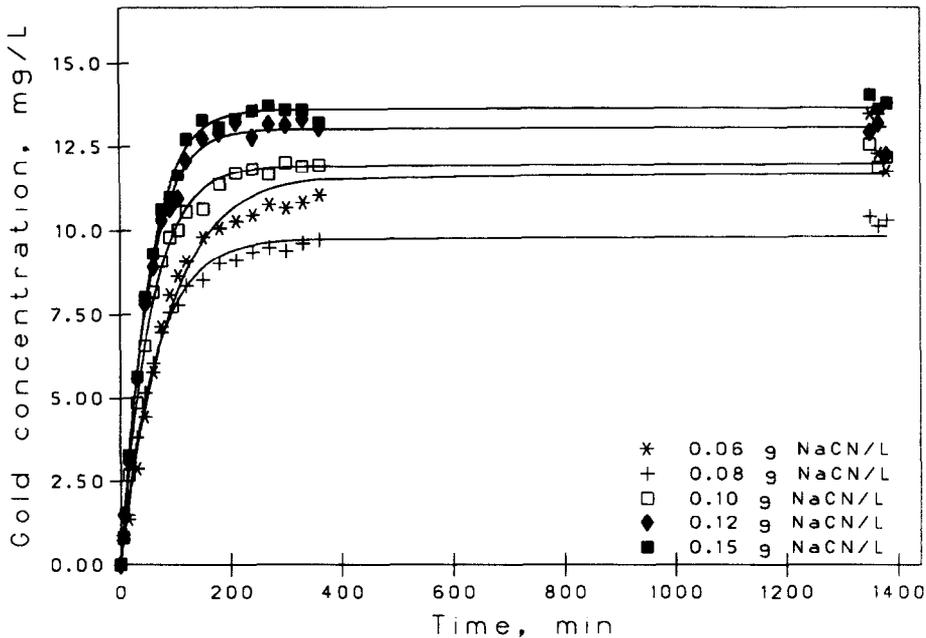


Fig. 4. The leaching of gold from ore sample 2 for different cyanide concentrations. The points represent the data, while the lines represent the fit of the mathematical model Eqs. (22) and (23) to the data. The parameters obtained from fitting the model to the data are presented in Table 1.

passivating material and the rate of leaching is rapid. As the passivating layer grows, and the proportion of surface that is free of passivating material shrinks, the rate of leaching slows dramatically. At this stage of the investigation the nature of the passive material is not known but it is thought to be a reaction product, possibly AuCN .

Fig. 3 and Fig. 4 show the results of the leaching of gold obtained in this study. The concentration of cyanide in the solution was varied between 0.1 and 0.4 g NaCN/l and 0.06 and 0.25 g NaCN/l for ore samples 1 and 2, respectively. The concentration of cyanide was automatically maintained at the set point value by the control system described in the experimental section. Therefore, concentrations of both oxygen and cyanide were maintained at a constant level throughout the experiment.

The points on Fig. 3 and Fig. 4 represent the experimental measurements, while the lines represent the solution to the model equations. These results indicate that the initial rate of reaction is dependent on the concentration of cyanide in the solution. The leaching curve reaches a plateau region after about 5 or 6 h; the leaching after this time continues at a much reduced rate. In addition, these results indicate that the extent of reaction, or the recovery, after about 23 h increases with increasing cyanide concentration. Since the concentrations of both cyanide and oxygen were maintained throughout the course of the batch experiment, the differences in the final recovery are not a result of the depletion of the amount of cyanide or oxygen in the solution.

The mathematical model of the leaching of gold is represented by Eq. (22) and Eq. (23). These differential equations were solved numerically using a Runge–Kutta–Fehl-

Table 1
Model parameters for ore sample 1

Cyanide concentration (g NaCN/l)	k_s (l/min)	k_2 (l/min)	k_{-2} (l/min)
0.1	5.81×10^{-3}	8.40×10^{-3}	3.29×10^{-4}
0.2	1.03×10^{-2}	9.97×10^{-3}	1.02×10^{-5}
0.3	1.11×10^{-2}	5.09×10^{-3}	4.37×10^{-4}
0.4	1.31×10^{-2}	5.49×10^{-3}	1.54×10^{-4}

berg routine written in C [23]. The parameters k_s , k_2 and k_{-2} were fitted to the data by minimising the sum of squared errors between the measured data and the model solution. The numerical minimisation routine used was the routine 'amoeba' [24], a downhill simplex method. The mathematical solution to the equations representing the model and the leaching data are in close agreement, indicating that the model is a good description of the leaching reaction. The parameters for each of the measured curves are given in Tables 1 and 2 for samples 1 and 2, respectively.

The electrochemical mechanism of leaching presented in the section on the mathematical model indicates that the rate constant, k_s , is dependent on the concentration of cyanide and oxygen (see Eq. (22)), and is given by:

$$k_s = \frac{3(k_a k_c)^{1/2} [O_2]^{1/2} [CN^-]^{1/2}}{\rho_{Au} RF}$$

This mechanism indicates that the rate of reaction, and hence k_s , is proportional to the square root of the concentrations of both oxygen and cyanide.

Previous models of the leaching reaction have asserted that the reaction is controlled by either the diffusion of cyanide or oxygen to the surface of the gold. If diffusion controls the rate of reaction, then the rate, and hence k_s , has to be proportional either to the concentration of cyanide or to the concentration of oxygen. If the order of reaction with respect to these reagents is not found to be equal to 1, then it is unlikely that the reaction is controlled by diffusion.

Table 2
Model parameters for ore sample 2

Cyanide concentration (g NaCN/l)	k_s (l/min)	k_2 (l/min)	k_{-2} (l/min)
0.06	8.25×10^{-3}	4.46×10^{-3}	1.82×10^{-5}
0.08	9.54×10^{-3}	7.92×10^{-3}	1.05×10^{-7}
0.1	1.31×10^{-2}	6.53×10^{-3}	1.50×10^{-6}
0.12	1.52×10^{-2}	5.52×10^{-3}	1.43×10^{-5}
0.15	1.53×10^{-2}	4.46×10^{-3}	3.88×10^{-6}
0.18	1.56×10^{-2}	4.77×10^{-3}	5.63×10^{-6}
0.20	1.88×10^{-2}	6.65×10^{-3}	1.51×10^{-5}
0.25	1.72×10^{-2}	9.63×10^{-3}	1.07×10^{-5}

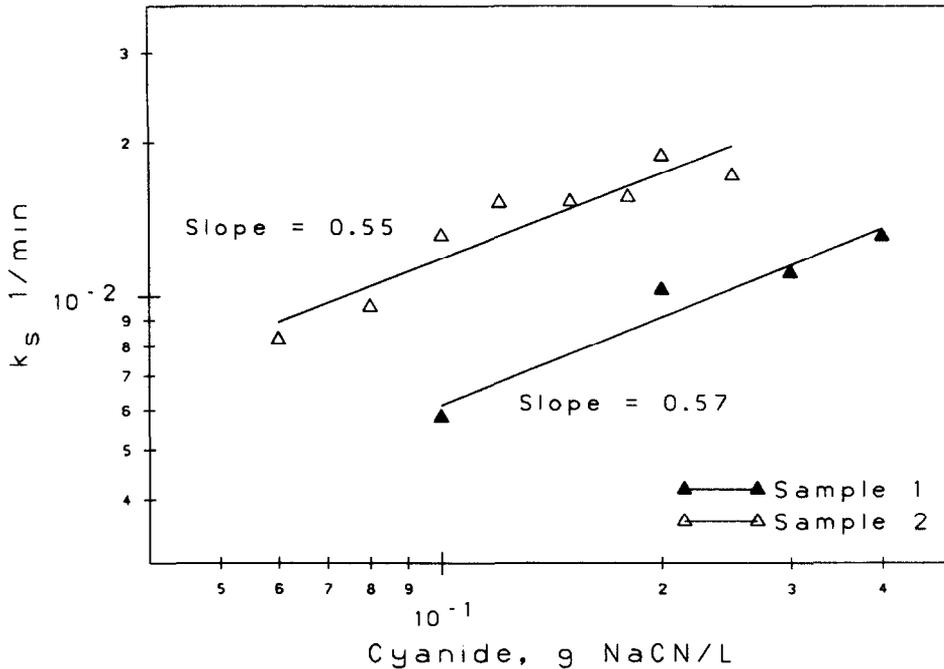


Fig. 5. The effect of the concentration of cyanide on the rate constant, k_s , for the two ore samples, indicating that the order of reaction is close to one-half with respect to cyanide.

Fig. 5 shows that the order of the leaching reaction with respect to cyanide is 0.55 and 0.57, which is very close to the value of one-half expected by the electrochemical mechanism. These results show clearly that the leaching of gold is controlled by the reaction at the surface of the gold and not by the diffusion of reactants (either cyanide or oxygen) to the surface of the gold.

McLaughlin and Agar [16] have presented results for the effect of oxygen on the rate of leaching of gold in cyanide solutions. Fig. 6 shows that their results indicate that the leaching reaction is close to one-half order in oxygen. This is expected from the mechanism of leaching that has been presented here, and confirms that the rate of reaction is controlled by the reaction at the surface and not by the diffusion of reactants to the gold surface.

The parameters k_2 and k_{-2} describe the formation and dissolution of the passivating layer on the surface of the gold. The parameter k_2 does not show any definite dependence on the concentration of cyanide in solution. The fit of the model to the data is not very sensitive to the parameter k_{-2} .

5. Conclusions

(1) We have presented an electrochemical mechanism of the leaching reaction that indicates that the initial rate of reaction is one-half order in the concentration of cyanide

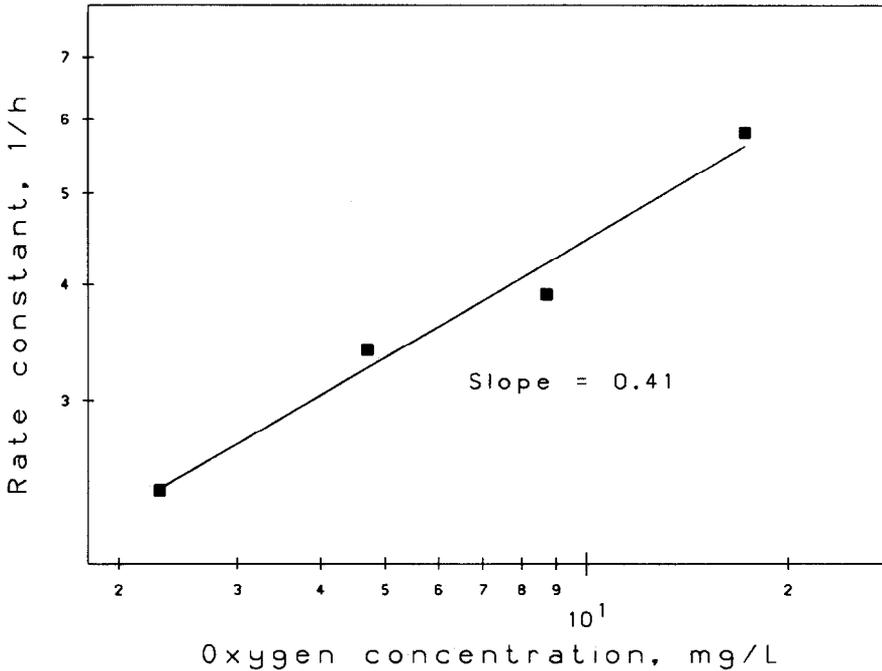


Fig. 6. The effect of the concentration of oxygen on the rate constant reported by MacLaughlin and Agar [15], indicating that the order of reaction is close to one-half with respect to oxygen.

and oxygen. This contrasts with the diffusion model of Habashi [2], which indicates that the reaction must be first order in either the concentration of cyanide or the concentration of oxygen.

(2) We have derived a mathematical model of the batch leaching of a particulate gold ore. This model is based on the shrinking-particle model, which describes the change in size of the mineral as the reaction proceeds. In addition, we have proposed that a layer of passivating material forms on the surface of the gold during the course of reaction. The passivating layer grows across the gold surface while the particle shrinks in size.

(3) We have presented results for the leaching of gold in which the concentration of both cyanide and oxygen were constant during the course of the reaction. These results are unique, since in most batch experiments the concentration of cyanide decreases either as a result of components of the ore that consume cyanide, or because of the hydrolysis of cyanide. In the rolling bottle tests, the concentration of oxygen is often depleted.

(4) Analysis of these results indicates that the mathematical model presented here is an excellent description of the leaching of gold. This confirms the basis of the model that there are two dominant reactions that occur on the gold surface: the dissolution reaction dominates in the initial stages of batch leaching, and the reaction representing the formation of a passivating layer dominates in the latter stages of batch leaching.

(5) Analysis of the rate constant for the dissolution reaction indicates that the mechanism of reaction is described by the electrochemical model presented here, and

not by the diffusion model presented previously by Kudryk and Kellogg [3] and Habashi [2].

Acknowledgements

The authors would like to thank Alan McCully and Anthony Stewart for performing the leaching experiments.

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