

## MODELING THE INFLUENCE OF SLURRY TEMPERATURE ON GOLD LEACH AND ADSORPTION KINETICS AT THE FORT KNOX MINE, FAIRBANKS, ALASKA

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### Abstract

The Fort Knox Mine is located in Alaska's interior where the average ambient air temperatures range from -24 °C in January to 16 °C in July. The mill processes a free milling gold ore utilizing both a gravity recovery circuit and conventional cyanide leach/carbon-in-pulp circuits. Plant slurry temperature cycles seasonally and allows for a unique opportunity to measure the impact temperature has on gold leach kinetics, carbon adsorption efficiency and cyanide destruction reactions. Mathematical models have been developed to accurately predict actual mill performance. This paper describes the development of the models and presents data that allow for a better understanding of the impact of circuit operating temperature on process efficiencies.

### Introduction

The Fort Knox Mine, located in the Fairbanks Mining District, 40-road km (25 miles) northeast of Fairbanks, Alaska, began commercial gold production in the first quarter of 1997. The average annual temperature at the site is -3.6 °C (26 °F) with daily temperatures averaging -23.8 °C (-10.9 °F) in January and 15.8 °C (60.4 °F) in July. The mine receives an average of 0.43 m (17 in.) of annual precipitation with most of the precipitation falling in the summertime and early fall. The average snow pack is 1.65 m (65 in.) and snow remains on the ground from early October until early April. The mine is accessible year round from Fairbanks via the Steese Highway and 9.7 km (6 miles) of well-maintained gravel road.

The Fort Knox gold deposit is hosted within a multi-phase granitic body with an elongated surface exposure. Gold is contained in milky-white quartz stockwork veins and veinlets, as well as along shears and fractures within

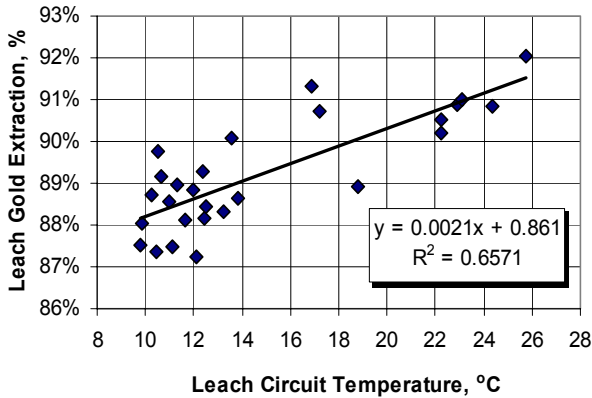
the granite. The quartz filled shears contain evenly distributed gold, generally less than 100 microns in size, while the gold in the milky-white stockwork veins and veinlets is similar in size, but has a more erratic occurrence.

The Fort Knox mill feed rate averaged 37,467 tpd (41,300 stpd) in 2003. The run-of-mine ore is crushed to minus 13 cm (5 in.) in a 1.9 m x 2.7 m (74 in x 105 in) primary gyratory crusher located near the pit, before being conveyed 0.8 km to the coarse ore stockpile at the mill site. The coarse ore is reclaimed from the stockpile and conveyed to a 10 m (34 ft) diameter by 4.5 m (15 ft) long SAG mill, which operates in close circuit with a 3.0 m x 7.3 m (10 ft x 24 ft) double deck vibrating screen. Screen undersize is processed through two Svedala 6 m (20 ft) diameter by 9 m (30 ft) long ball mills operated in closed circuit with twenty, 66 cm (26 in.) diameter cyclones. The SAG mill is driven by two 5,200 kw (7,000 hp), synchronous, electric motors controlled by LCI drives to provide variable speed control. Each ball mill is powered by a fixed speed, 5,200 kw (7,000 hp), synchronous electric motor. The final product from the grinding circuit was designed to be 80% passing 149 microns (100 mesh).

Pinched sluices, located in each of the ball mill discharge launders, are used to produce approximately 436 tph (480 stph) material that is processed through two Knelson concentrators, where approximately 15 percent of the total gold production is recovered by gravity concentration. Gravity tailings are returned to the grinding circuit for further comminution. The grinding circuit product is processed through a high capacity thickener, which produces a 50-54% (w/w) solids underflow that is pumped to the seven stage cyanide leach circuit. The slurry discharging from the leach circuit is processed through a conventional, six stage, carbon-in-pulp (CIP) circuit, where the dissolved gold is adsorbed onto granular activated carbon. At present, the plant is

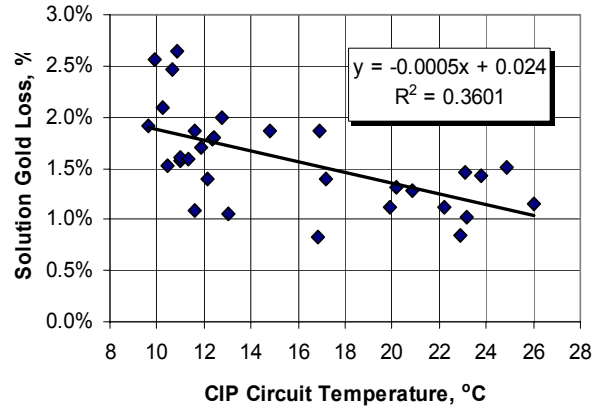


In addition, it became apparent that variations in leach circuit gold extraction were correlated to circuit operating temperature. Figure 3a contains a simple regression of leach gold recovery and circuit operating temperature during the initial years of operation at the Fort Knox mill. The results suggested that although a significant relationship existed between leach temperature and gold extraction, a more sophisticated model was needed to further explain the variability in the actual plant results



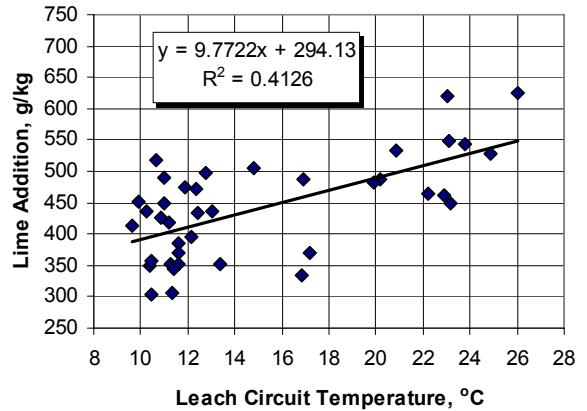
**Figure 3a. Simple regression between leach circuit gold recovery and leach circuit temperature (1998-2001).**

Variations in mill solution gold losses have also trended seasonally (Fig.3b) and can be partially explained by a simple linear relationship with solution gold losses (expressed as a percent of leach feed ounces) being dependent on leach/CIP circuit operating temperature. Development of the detailed model describing leach and carbon adsorption kinetics is included in this paper.



**Figure 3b. Simple regression between CIP solution gold loss and CIP circuit temperature (1998-2001).**

The relationship between circuit operating temperature and fluctuations in reagent addition rates were also observed during the initial years of operation at the Fort Knox mill. Figure 4a contains the relationship between the lime addition rate and circuit operating temperature. Additional variation in the lime addition rate can be explained by variations in circuit pH as a second dependent variable.



**Figure 4a. Simple regression between leach circuit lime addition and leach circuit temperature (1998-2001).**

The SO<sub>2</sub>/air cyanide destruction circuit is another area where reagent addition is correlated with circuit operating temperature. Figure 4b contains the simple regression model representing this relationship.

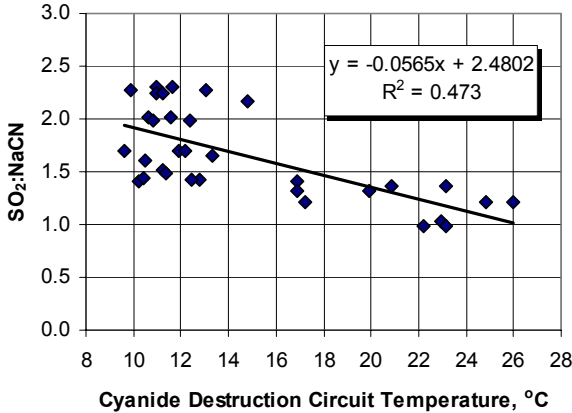
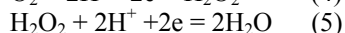
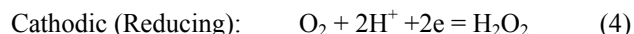
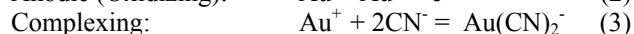
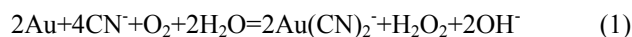


Figure 4b. Simple regression between SO<sub>2</sub> addition and cyanide destruction circuit temperature (1998-2001).

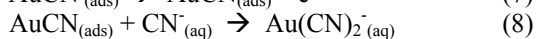
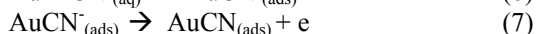
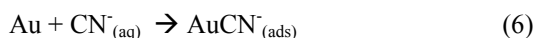
## Model Development

### *Gold Dissolution in Cyanide Solution*

The mechanism for gold dissolution using cyanide as the complexing agent has been studied extensively with general consensus that the reaction is electrochemical in nature (Christy, 1896; Boonstra, 1943; Thompson, 1947; Kirk *et al.*, 1978; Lin and Chen, 2001). Additional gold cyanidation evaluations have also been conducted (Kudryk and Kellogg, 1954; Habashi, 1967; Wadsworth, 1991) with emphasis placed on reaction kinetics. The role of the primary reactants ( $O_2$  and  $CN^-$ ) can be described by evaluating the individual anodic and cathodic half reaction equations. Equation (1) represents the overall reaction (Elsner's equation), while equations (2) and (3) express the anodic reaction and complexing reaction, respectively. Equations (4) and (5) represent the cathodic reactions.



The anodic and complexing reactions (gold oxidation) have been further defined as follows (Cathro and Koch, 1964; MacArther, 1972; Thurgood *et al.*, 1981; Wadsworth, 1991; Lin and Chen, 2001):



where the subscript (ads) refers to surface adsorbed species and (aq) refers to the aqueous species.

Kudryk and Kellogg (1954) concluded that the kinetics of gold cyanidation were directly related to the concentration of the complexing agent (cyanide) under one regime, while the kinetics are controlled by the concentration of the oxidant (oxygen) in another.

Based on the anodic and cathodic reactions listed above, they concluded that 2 moles of cyanide ion were required to dissolve one mole of gold and release one mole of electrons in the anodic reaction. It was also concluded that one mole of oxygen (when reduced to hydroxyl ions) would consume 4 moles of electrons, that the reaction was essentially 100 % efficient in discharging oxygen, and that the intermediate formation of hydrogen peroxide did not occur in significant amounts. This

resulted in the theoretical cyanide to oxygen molar ratio, 8:1.

Deitz and Halpern (1953) evaluated the kinetics of the dissolution of silver in sodium cyanide solution and concluded that the reducing reaction described by equation 4 did not appear to participate to any extent. The conclusion was based on results of tests, where  $H_2O_2$  was added to the solution and did not affect the gold dissolution rate. Additionally their test results indicated that the transition from the region, where the rate is controlled by the transport of  $CN^-$  to the region of control by the transport of  $O_2$ , occurs at a ratio of concentration  $[NaCN]:[O_2]$  of 4.4.

Habashi (1967), upon review of previously published works (including Kudryk and Kellogg, 1954), concluded that the intermediate formation of the  $H_2O_2$  and hydroxyl ion expressed by equation (4) was the final step in the cyanidation reaction and that only two electrons would be required to reduce the oxygen. Habashi proposed that the ratio of the molar concentrations of cyanide to oxygen, at which the rate controlling concentration changes from cyanide to oxygen, was 6:1 (9.1 ppm NaCN:1 ppm  $O_2$ ) and ranged from 4.6:1 to 7.4:1. This value also represents the rate at which the diffusion of both reactants should be at their maximum.

Wadsworth (1991) presented data indicating that the reduction of hydrogen peroxide begins at different potentials for various metals. He concluded that the rate at which peroxide diffuses away from the metal surface may also influence the effective use of oxygen and it is likely that both the 4-electron and 2-electron processes are occurring simultaneously and that the number of electrons transferred varies with potential.

Ling *et al.* (1996) presented data from cyanidation experiments on a particular gold ore, where the objective was to decouple the effects of free cyanide  $[CN^-]$  and dissolved oxygen  $[O_2]$  concentration. They found the leach rate reached a plateau when  $[CN^-]$  was higher than 100 ppm on tests performed with  $[O_2]$  at 8.5 ppm, and an oxygen to free cyanide ratio of 11.8:1.

Heath and Rumball (1998) suggested a method for determining whether gold leaching in CIP/CIL circuits is limited by the lack of either oxygen or cyanide. They presented data generated using a gold (96%)/silver (4%) alloy disc electrode placed in leaching pulp, with its corrosion potential measured against a reference electrode. The results suggested the optimum cyanide:oxygen ratio was approximately 10.5 ppm  $[NaCN]$  to 1 ppm  $[O_2]$  (6.9:1 molar ratio). Their conclusions were supported by Wadsworth's (2000) findings that silver surface reactions used the 4-electron process while oxygen reduction on the gold surface used the 2-electron processes. They suggested that the difference between the 6:1 molar ratio proposed by

Habashi and their finding of 6.9:1 was the result of using an alloy electrode in pulp rather than a pure gold electrode evaluated in clear solution. They also noted that previous measurements were voltametric, with the gold electrode forced to be either an anode or a cathode, rather than both simultaneously occurring as in actual plant conditions.

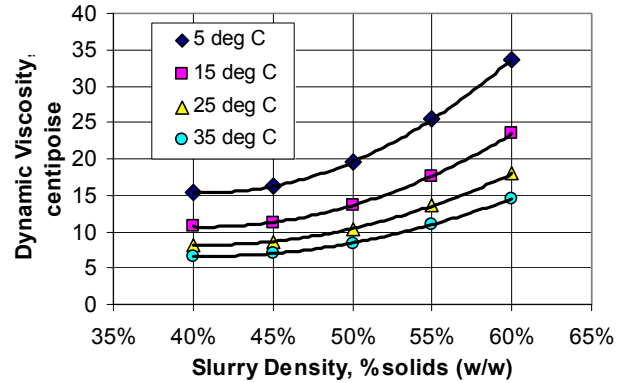
Heath and Rumball (1998) repeated the procedure on a variety of Western Australian CIP/CIL slurries and determined that the cyanide to oxygen ratio was essentially unchanged by the pulp type and consistent with the results on pure solution. They suggested that the actual diffusion rate of oxygen and cyanide to the gold particle surface under plant conditions will be significantly different from that measured in the laboratory. However, the diffusion rate of both the oxygen and cyanide can be expected to be impacted by the same amount and the optimum cyanide to oxygen ratio should remain unchanged.

**Effect of Temperature on Leach Slurry Rheology**

Rheology studies of Fort Knox leach feed materials were completed, in order to provide data for the engineering and design phases of the project (Link, 1993). Six slurry runs were completed in an extrusion rheometer at temperatures ranging from 18 °C to 26 °C (64 °F to 78 °F) and slurry densities ranging from 41.9% solids (w/w) to 61.4% solids (w/w).

The results indicate that the slurries are Bingham plastics over all expected operating conditions. Results also indicated that slurry dynamic viscosities would be significantly affected by both the density (% solids w/w) and the temperature of the slurry. Slurry dynamic viscosity increased slowly up to a value of approximately 50% solids (w/w) at which point the rate of increase then accelerated up to a value of approximately 56% solids (w/w). Additionally, as slurry temperatures decreased from 26 °C (70 °F) to 18 °C (46 °F), the dynamic viscosities increased by as much as 67 percent and the Reynolds number of mixing dropped from 50,552 to 33,220.

Although no laboratory work was done with the same slurry at different temperatures, the effects of temperature on slurry viscosity are similar to those for other fluids and can be predicted by a simple power law relationship over usefully large temperature ranges (Link, 1993). The results of the six tests were used to compute rheologic constants that were then used to calculate the effect of density and temperature on slurry dynamic viscosity. Figure 5 contains these results, which indicate that variations in leach circuit slurry densities typical for the Fort Knox mill (48 to 51% solids w/w) will have significantly less impact on dynamic viscosity, than the effect due to variations in leach circuit temperature.



**Figure 5. Summary of 1993 rheology studies on Fort Knox leach feed material.**

It is proposed that these variations in slurry rheology result in measurable impacts to reactions controlled by diffusion within the Fort Knox mill’s leaching/CIP circuits, and that these impacts can be predicted using temperature as the independent variable, since a direct measurement of slurry viscosity was not available in the plant data.

**Effect of Temperature on Leach Oxygen Concentration**

Habashi (1970) described the cyanidation process as a heterogeneous reaction taking place between three phases; gold (solid), aqueous NaCN (liquid), and oxygen (gas). Since the rate at which oxygen is transferred from the gaseous phase to the liquid phase is much faster than the other reactions taking place, the process is reduced to a solid-liquid reaction. The gold dissolution rate increases with temperature, as a result of increased surface reaction and diffusion rates of reactants and products, up to a maximum of 85 °C (Marsden and House, 1992). Deitz and Halpern (1953) evaluated the rate of silver dissolution in NaCN solutions at temperatures ranging from 24 °C to 110 °C. They generated an Arrhenius plot and determined the reaction rate was linear over the entire temperature range tested, with a slope that indicated the activation energy was low and the rate was controlled by a diffusion process.

Ling *et al.* (1996) presented data that showed the oxygen level maintained during the 48 hour laboratory leach tests was mainly affected by variations in temperature rather than the rate of oxygen consuming reactions, the rate of oxygen mass transfer, or the ionic strength.

At the Fort Knox mill, the seven leach tanks, 16.5 m (54 ft) in diameter by 14.6 m (48 ft) tall, are constructed of carbon steel and are covered with an insulated cover that allows for a slight partial pressure to be maintained over the slurry. The tanks are located outdoors with no insulation other than the covers. The oxygen is added as

atmospheric air injected into the tanks via spargers located near the bottom of the tanks. The leach circuit's dissolved oxygen concentration [O<sub>2</sub>] data are presented in Figure 6. The data suggest that the leach [O<sub>2</sub>] can be expressed as a function of slurry temperature.

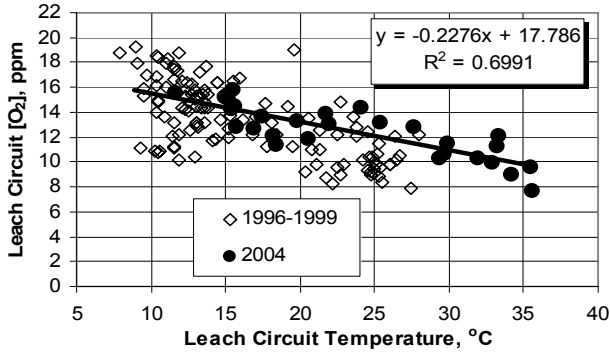


Figure 6. Historical Fort Knox leach circuit [O<sub>2</sub>] as a function of leach circuit temperature.

The reaction rate has been shown to be a function of the circuit oxygen concentration (Habashi, 1967; Ling, et al., 1996; Rubisov, et al., 1996; Fang, et al., 1998). However, in the Fort Knox leach circuit, since the dissolved oxygen concentration is primarily dependent on circuit operating temperature, any expression of the rate constant as a function of temperature will also account for variations in oxygen concentration

Assuming that the optimum ratio at Fort Knox is 11 ppm NaCN to 1 ppm O<sub>2</sub>, the rate limiting conditions can be expressed as a function of leach slurry temperature. Figure 7 contains this relationship for the Fort Knox leach circuit.

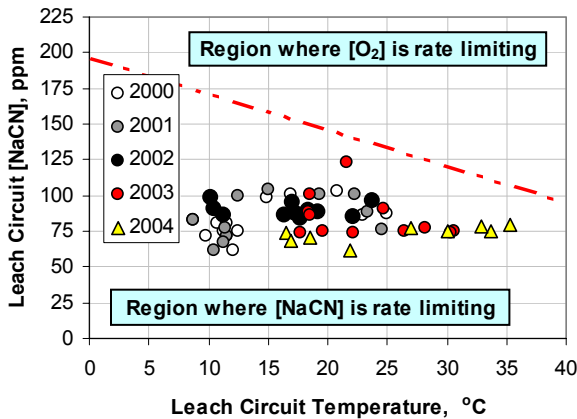


Figure 7. Theoretical rate controlling regions expressed as a function of leach circuit temperature.

Also included in Figure 7 is the actual average monthly leach circuit NaCN concentrations maintained in the Fort Knox leach circuit in recent years. The data suggest under all normal operating conditions, gold cyanidation is being controlled by cyanide diffusion and the reaction rate will be a function of the cyanide concentration.

In general, the leach circuit has been operated at NaCN concentrations ranging from 70 ppm to 80 ppm during periods when the mill is processing straight Fort Knox ore. Periods where the concentration was higher than 80 ppm are primarily associated with processing blends of Fort Knox and True North ores. All new cyanide is added at leach tank #1 where the pH is maintained between 10.2 and 10.4 through dry lime addition to the grinding circuit.

Figure 8 contains a timeline of the historic leach concentrations and indicates that only a minimal reduction in [NaCN] is observed in the leach circuit (5-10%) when processing straight Fort Knox ore. The majority of the cyanide loss is occurring in the CIP circuit. This is consistent with the findings of Adams (1990), who evaluated the kinetics of cyanide loss in a typical leach/CIP process. He observed only minor loss in the absence of activated carbon with fairly high losses when carbon was present. The losses were due to adsorption, to some extent, onto activated carbon and to a carbon-catalysed oxidation of cyanide to cyanate. For periods when True North ore is blended with Fort Knox ore in the mill feed (April 2001 – March 2004), more dramatic cyanide losses are observed. These losses are the result of cyanide consuming constituents (base metals and sulfides, Adams, 1990) in the True North ore.

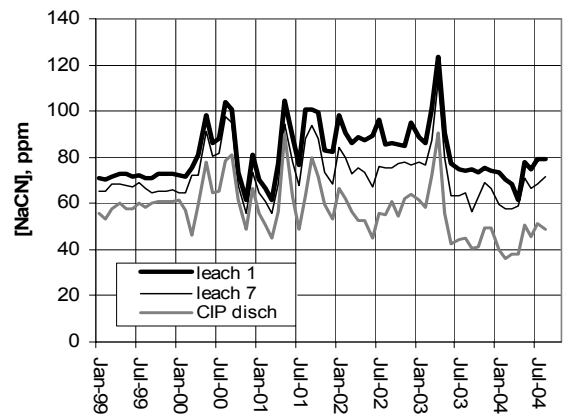
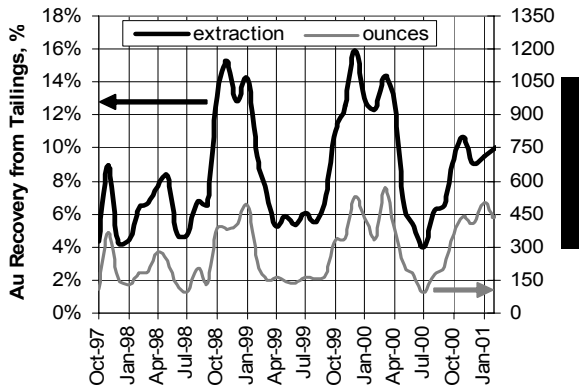


Figure 8. Historic Fort Knox leach/CIP circuit NaCN concentrations; (2000–2004)

**Effect of Temperature on Gold Leach Rate**

Plant tailings are sampled and analyzed at room temperature on a daily basis at the Fort Knox mill. In one analysis, bottle roll leach tests are performed on tailings slurry samples to determine the remaining cyanide soluble gold content. The average monthly results, presented in Figure 9, indicate the seasonal variations became more pronounced after mill throughput rates increased during 1998 and further substantiates the proposed relationship between leach kinetics and circuit operating temperature.



**Figure 9. Monthly cyanide soluble gold losses in solid tailings at the Fort Knox mill; (1997–2001). Recovery expressed as percent of gold in leach feed.**

The model form chosen to estimate leach gold extraction at the Fort Knox mill is given in Equation 9 under conditions of constant temperature, cyanide concentration and mill head grade. This is the form of the Mintek expression described by Nicol *et al.* (1984).

$$\frac{d[Au]}{dt} = -k_{leach} ([Au]_t - [Au]_{\omega})^n \quad (9)$$

where  $[Au]_t$  and  $[Au]_{\omega}$  are the solid gold concentration at time ( $t$ ) and unleachable gold concentration, respectively. Integration of equation (9), with the initial condition of  $[Au]_t = [Au]_o$  at  $t = 0$ , yields the following general relationship, when the reaction order is not equal to 1:

$$k_{leach} = \frac{1}{(n-1)t} \{ ([Au]_t - [Au]_{\omega})^{(1-n)} - ([Au]_o - [Au]_{\omega})^{(1-n)} \} \quad (10)$$

By rearranging equation (10), a general expression for calculating  $[Au]_t$  takes the following form:

$$[Au]_t = \left\{ (n-1)k_{leach} t + \frac{1}{([Au]_o - [Au]_{\omega})^{(n-1)}} \right\}^{-1/(n-1)} + [Au]_{\omega} \quad (11)$$

Finally, the gold extraction ( $X$ ) is calculated using Equation (12):

$$X = \frac{([Au]_o - [Au]_t)}{[Au]_o} \quad (12)$$

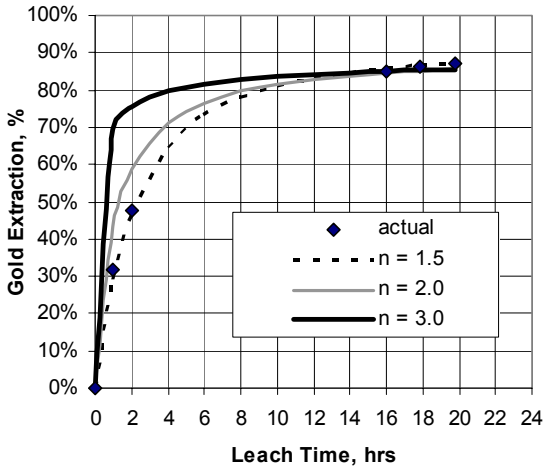
The model indicates that the reaction rate is a function of the difference between the gold grade  $[Au]_t$  at time ( $t$ ) and the unleachable gold concentration  $[Au]_{\omega}$ . Ling *et al.* (1996) found the unleachable gold concentration at infinite leach time  $[Au]_{\omega}$  was dependent only on the particle size distribution of the ore tested. The unleachable gold concentration in the proposed Fort Knox model has been determined to be a function of the ore particle size represented by the ore  $P_{80}$  (microns) and mill feed grade  $[Au]_{HG}$ , (mg/kg). Although variability exists in the data ( $R^2 = .39$ ), the multiple linear relationship presented in equation (13) provides the baseline required to account for a known dependent variable in the leach circuit performance model.

$$[Au]_{\omega} = 0.00033(P_{80}) + 0.0312[Au]_{HG} - 0.0267 \quad (13)$$

The order of the rate function ( $n$ ) has been described by various authors. Rees and Van Deventer (2001) found  $n = 1.28$  for the relatively simple oxide ore analyzed under controlled laboratory conditions. McLaughlin and Agar (1991) used the first order form of the equation to accurately model the rate of gold extraction by cyanidation on four distinct ore samples. Ling *et al.* (1996) presented data from cyanidation experiments on a particular gold ore (where the objective of the experiment was to decouple the effects of free cyanide and dissolved oxygen concentrations) and suggested a version of the model where  $n = 1.5$ . Nicol *et al.* (1984) indicated the reaction was actually 2<sup>nd</sup> order.

Laboratory bottle roll test procedures were developed to simulate actual plant gold extraction by taking into account plant operating conditions with respect to ore particle size, cyanide concentration, slurry density (w/w) and gravity recovery efficiency. The duration of the test is calculated based on actual plant throughput rates and were intended to predict total gold extraction. However, the tests are performed at room temperature (20 °C) and do not provide data to evaluate the effect of temperature on the cyanidation rate.

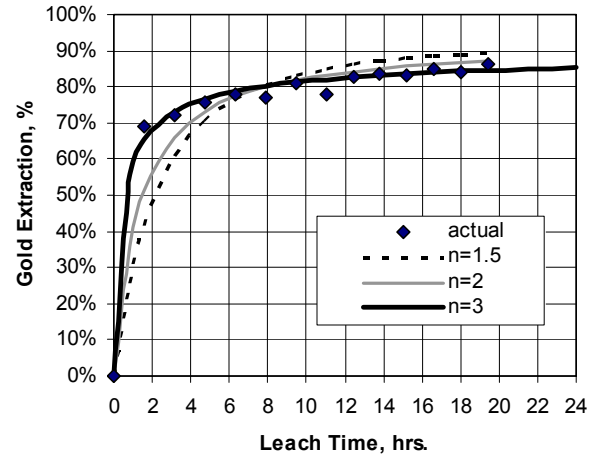
Figure 10 contains the laboratory data and the results estimated from the three rate orders evaluated. The results indicate that in laboratory bottle roll tests, the order of the rate function, that best fits the actual gold extraction from Fort Knox ore, is 1.5 which is consistent with the work of Ling *et al.* (1996).



**Figure 10. Comparison of 2004 laboratory bottle roll data and the order ( $n$ ) of the rate equation (Equation. 9).**

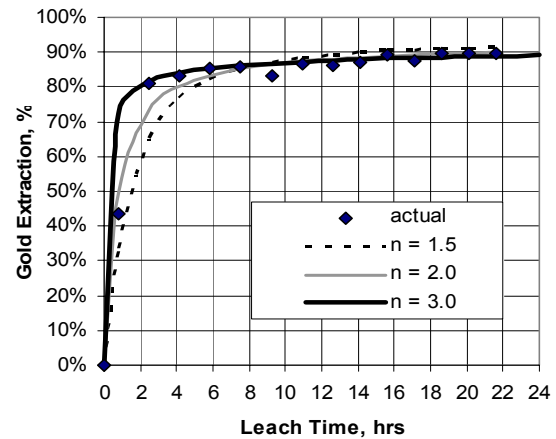
A detailed leach/CIP sampling program is performed at the Fort Knox mill on a weekly basis and used to monitor actual plant performance. Each profile represents a snap shot of the cyanide leach circuit for that given time and alone does not supply sufficient data to do kinetics calculations. However, an average of numerous profiles allows sufficient data to develop a baseline model. The value for the rate constant  $k$  was calculated for each of the 13 sample points, representing the seven leach and six CIP tank discharges. The average rate constant from the 13 calculations was used for the remaining model calibration.

The value for  $n$  could then be determined by minimizing the error term when the model estimated value for  $[Au]_t$  was regressed against the actual values determined from the weekly profile data. Figure 11a contains results obtained when the relationships described by Equations 9 through 12 were used to fit the actual plant data collected between 1997 and 1999, when the plant slurry temperatures averaged 12 °C and ranged from 8 °C to 15 °C).



**Figure 11a. Comparison of plant data and the order ( $n$ ) of the rate equation (Equation 9), (1997-1999).**

Figure 11b contains similar data for the periods during 2004 when the mill was processing straight Fort Knox ore, when slurry temperatures averaged 31 °C, and ranged from 29 °C to 34 °C.



**Figure 11b. Comparison of plant data and the order ( $n$ ) of the rate equation (Equation 9), (2004).**

The results suggest that a third order rate equation ( $n = 3.0$ ) provides the best fit for both data sets with the coefficient of correlation ( $R^2 = 0.996$  and  $0.999$ , respectively). This value is significantly different from that calculated from the laboratory results (Figure 10) and indicates that the order of rate equation is a function of physical plant conditions and not the mineralogy of the ore being processed. Therefore, the baseline form of the gold leaching model that best estimates actual Fort Knox

plant performance is a 3<sup>rd</sup> order equation that can be expressed as follows:

$$\frac{d[Au]}{dt} = -k_{leach} ([Au] - [Au]_o)^{3.0} \quad (14)$$

Integration of equation (14), with the initial condition of  $[Au]_t = [Au]_o$  at  $t = 0$ , yields the following:

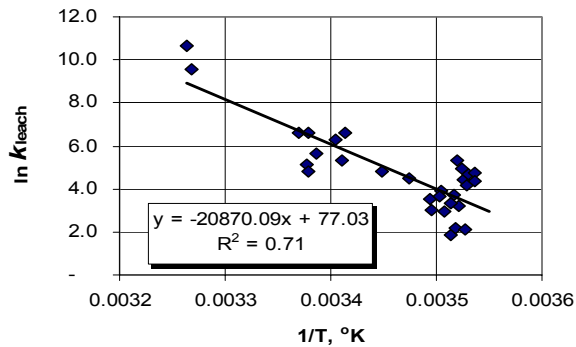
$$k_{leach} = \frac{0.5}{t} \{ ([Au]_t - [Au]_o)^{-2.0} - ([Au]_o - [Au]_o)^{-2.0} \} \quad (15)$$

By rearranging equation (15),  $[Au]_t$  can be calculated for the Fort Knox circuit as follows:

$$[Au]_t = \left[ 2.0 k_{leach} t + \frac{1}{([Au]_o - [Au]_o)^{2.0}} \right]^{-0.50} + [Au]_o \quad (16)$$

where:  $[Au]$  is expressed in mg/kg and  $(t)$  is expressed in hours.

Historic daily operating data, as well as laboratory results, indicate that gold extraction at Fort Knox is a function of leach NaCN concentration and temperature in addition to mill head grade. By plotting the logarithm of the rate constant against  $1/T$  (Arrhenius plot), the relationship between the rate constant and temperature (Figure 12) can be established.



**Figure 12. Arrhenius plot of the effect of temperature on the gold leach rate constant.**

An expression for the rate constant was then developed using the Arrhenius equation, adjusted to account for variations in the leach cyanide concentration. The rate constant  $k_{leach}$  is calculated using Equation 17.

$$k_{leach} = \left\{ \frac{[NaCN]_{actual}}{[NaCN]_{ave}} \right\} 2.84 \times 10^{33} e^{-20,870(1/T)} \quad (17)$$

where:  $[NaCN]_{actual}$  = actual cyanide concentration, ppm  
 $[NaCN]_{ave}$  = average cyanide concentration, ppm  
 $T$  = temperature, °K

The rate constant calculated from Equation 17 was then used in Equation 16, in order to estimate the mill's final solid tailings loss,  $[Au]_t$ .

#### Effect of Temperature on CIP Circuit Efficiency

Nicol *et al.* (1984) indicated that the rate at which gold disappears from solution can be described in terms of an apparent first-order process over short time periods (less than 12 hours). At the Fort Knox mill, CIP retention time varies from 6 to 10 hours depending on variations in mill processing rates and falls well within the criteria described by Nicol. Leach/CIP circuit profiles have been performed on a weekly basis, since the Fort Knox mill began commercial operation in 1997. The CIP solution gold concentration can be estimated using the following equation:

$$\frac{d[Au]}{dt} = -k_{CIP} [Au]_t \quad (18)$$

Integration of equation (18), with the initial condition of  $[Au]_t = [Au]_{L7}$  at  $t = 0$ , yields the following equation:

$$\ln \frac{[Au]_t}{[Au]_{L7}} = -k_{CIP} t \quad (19)$$

where:  $[Au]_t$  = gold concentration in solution at time  $t$   
 $[Au]_{L7}$  = initial gold concentration in solution  
 $t$  = contact time (min)

By rearranging equation (19), the solution gold concentration  $[Au]_t$  can be calculated for the discharge of each CIP tank in the Fort Knox circuit.

$$[Au]_t = [Au]_{L7} e^{-k_{CIP} t} \quad (20)$$

Each of the leach profiles described previously were viewed as a snapshot of a steady state operating condition and provides a measurement of the gold concentration remaining in the solution at the discharge of each of the six stages in the CIP circuit. The time used at each point was based on the tank volume and average circuit conditions with respect to circuit feed rate and circuit density measured during the profile. A typical solution profile is contained in the Figure 13.

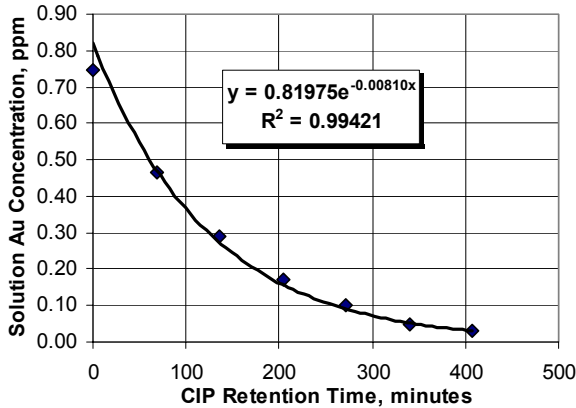


Figure 13. Typical 1<sup>st</sup> order rate relationship CIP profile.

By plotting the gold concentration with respect to time and using a nonlinear regression analysis, a relationship was determined that estimated the solution gold concentration at the discharge of each CIP tank. Although the approach provided a good fit to the weekly data, variability was found to exist in the regression slope calculated from month to month. The high variability suggested the actual slope was dependent on additional variables.

Fleming and Nicol (1984) evaluated the influence that a number of variables had on the rate of gold cyanide loading onto activated carbon. They concluded that mixing efficiency and slurry rheology were the most important parameters governing the adsorption rate. Since the Fort Knox mill has operated under consistent mixing conditions since startup, the variance in the CIP tailings solution gold concentrations is likely due to changes in slurry rheology that have been shown to be a function of slurry temperature.

The initial variable evaluated to explain the variance in  $k_{CIP}$  was circuit operating temperature. By plotting the logarithm of the rate constant against  $1/T$  (Arrhenius plot), the relationship can be established. The results suggested that the explained variance, 60%, may be due to variations in the slurry rheology as predicted by changes in the slurry temperature. The results of the Arrhenius plot of the plant data are shown in Figure 14.

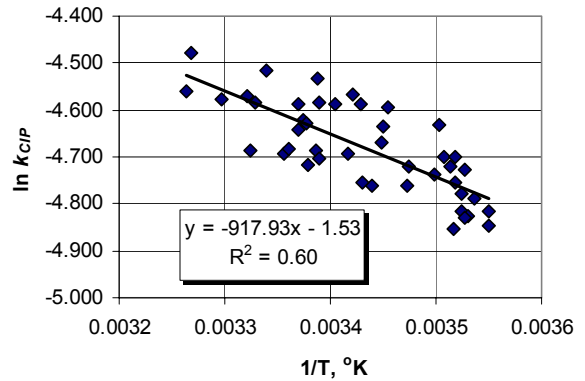


Figure 14. Arrhenius plot of the effect of temperature on the CIP model rate constant.

The relationship between the slope and the circuit temperature was then incorporated into the original model and provided a significantly better approach for estimating final solution gold concentrations in the Fort Knox CIP tails. The new relationship was again used to recalculate the monthly data. The remaining variance was reevaluated with the most significant relationship existing between the variance and the average carbon advance rate used during the individual months. This relationship is shown in Figure 15.

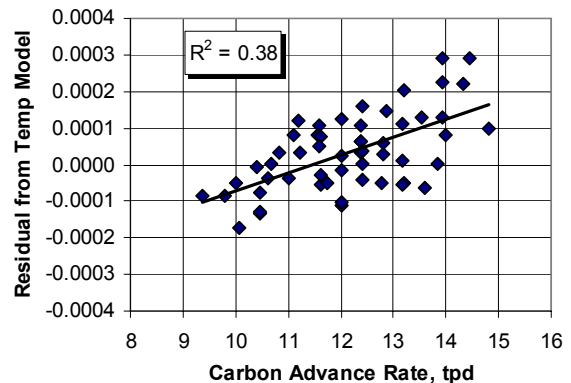


Figure 15. Model error term vs. carbon advance rate.

The rate constant, estimated using the Arrhenius equation, was then adjusted to account for variations in the CIP carbon advance rate. The rate constant,  $k_{CIP}$ , was calculated using Equation 21.

$$k_{CIP} = \left\{ \frac{AR_{\text{actual}}}{AR_{\text{ave}}} \right\} 0.22 e^{-918 (1/T)} \quad (21)$$

where:  $AR_{\text{actual}}$  = actual CIP carbon advance rate, tpd  
 $AR_{\text{ave}}$  = average CIP carbon advance rate, tpd  
 $T$  = temperature, °K

The rate constant calculated from equation 21 was then used in Equation 20, in order to estimate the final CIP solution gold loss.

### Model Predictions and Discussion

The 3<sup>rd</sup> order rate model (Equation 16) developed for the Fort Knox leach circuit gold dissolution kinetics was used to estimate the gold grade of the solid tailings between 1998 and 2004. The comparison of actual vs. predicted solid tailings grade (Equation 16) is displayed in Figure 16. The estimated values provide a reasonable fit to actual plant results. Areas of high variability are likely due to a poor estimate of  $[Au]_0$  and not associated with the form of the model. This is most apparent in the 2001 through 2003 data, when the mill processed True North ore that is more variable with respect to sulfide mineral and refractory gold content (Hollow *et al.*, 2003a, 2003b).

It is also likely that the rate constant ( $k_{leach}$ ) is significantly different, when the mill is processing a blend of Fort Knox and True North ores, since blended ore has been shown to be sensitive to leach cyanide concentration,  $[NaCN]$  (Hollow *et al.*, 2003a, 2003b). Since the model developed here was based on relationships established while the mill was processing straight Fort Knox ore, additional work will be required to account for variations in ore mineralogy.

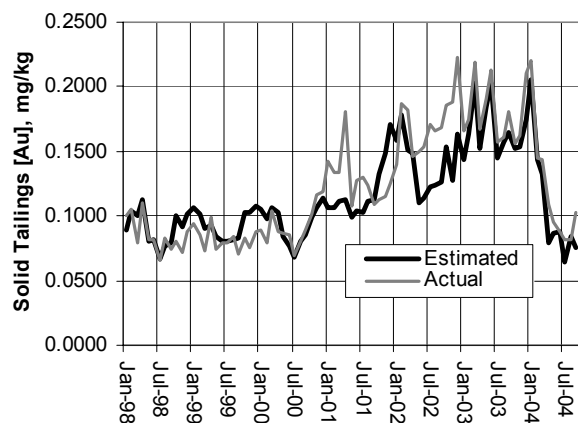


Figure 16. Comparison of actual plant solid tailings assays to model predicted values.

The 1<sup>st</sup> order rate model (Equation 20) for the CIP circuit performance was used to estimate solution tailings gold concentrations between 1999 and 2004 and provided a reasonable fit to actual plant solution tailings gold concentrations. This comparison is displayed in Figure 17.

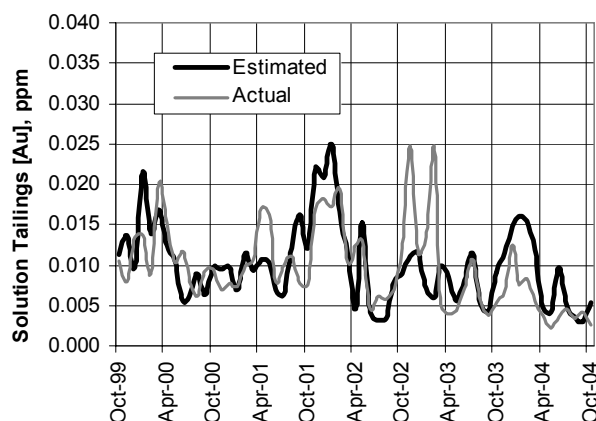


Figure 17. Comparison of actual plant solution tailings gold concentration to model predicted values.

The proposed CIP model, which accounts for variations in circuit operating temperature and carbon advance rates, provides a reasonable estimate of actual plant performance and provides a good tool for evaluating upset conditions. In general, the remaining variance in the model can be attributed to the error in the prediction of the CIP feed solution concentration,  $[Au]_0$ , estimated from the leach model. The primary source of this error is in the estimate of the unleachable solid gold concentration,  $[Au]_0$ . When the data in Figure 16 is compared to that of Figure 15, it can be seen that when the actual solid tailings gold concentration is significantly understated by the leach model, the CIP solution model will predict higher than actual final solution tailings gold concentrations. Additionally, variations in CIP circuit carbon concentration (g/l) and carbon activity likely add to the error in the model and warrant further investigations.

The rate constants calculated with Equations 17 and 21 were used in Equations 16 and 20 to predict the effect of temperature on overall Fort Knox mill recovery under average conditions. Table 1 contains a summary of the mill parameters used in the evaluation and Table 2, the models' outputs.

Table 1. Mill conditions evaluated

Parameter	
mill feed rate, tpd	37,467
mill feed grade, mg/kg	0.960
gravity gold recovery, %	16.0%
leach particle size $P_{80}$ , microns	201
leach density, % solids (w/w)	52%
leach $[NaCN]$ , ppm	75
carbon advance rate, tpd	12

The results contained in Table 2 indicate that the leach gold extraction increases from 86.5% to 89.4% when the plant slurry temperature increases from the 10.0 °C (typical of winter operation at the Fort Knox mill) to 26.7 °C (typical temperatures reached during summer operation). This represents a difference in daily leach gold production of approximately 33 ounces.

**Table 2.** Predicted mill grades and losses

Parameter	10.0 °C	26.7 °C	37.8 °C
leach feed grade, mg/kg	0.81	0.81	0.81
leach solid tailings, mg/kg	0.11	0.08	0.07
CIP solid tailings, mg/kg	0.10	0.08	0.07
unleachable gold grade, mg/kg	0.07	0.07	0.07
CIP solution tailings, ppm	0.011	0.007	0.003
solid tailings loss <sup>1</sup> , %	12.0%	9.8%	8.8%
solution tailings loss <sup>1</sup> , %	1.5%	0.9%	0.4%
<b>total gold recovery, %</b>	<b>86.5%</b>	<b>89.4%</b>	<b>90.8%</b>
solid tailings loss, oz/day	139	113	102
solution tailings loss, oz/day	17	10	4
total gold loss, oz/day	156	123	106

<sup>1</sup> losses are percent of leach feed ounces

### Conclusions

- Presented was an evaluation of the primary rate determining factors affecting gold recovery in the Fort Knox mill's leach/CIP circuit.
- It is proposed that variations in slurry rheology result in measurable impacts to reactions controlled by diffusion within the Fort Knox mill's leach/CIP circuits, and that these impacts can be predicted using temperature as the independent variable.
- Historically, the leach cyanide concentration, [NaCN], has been maintained at levels where the [NaCN] is rate limiting; the oxygen concentration, [O<sub>2</sub>], is not rate limiting.
- The following 3<sup>rd</sup> order rate model provides an estimate of solid tailings gold concentration [Au]<sub>t</sub> that best fits the actual plant data:

$$[Au]_t = \left\{ 2.0 k_{leach} t + \frac{1}{([Au]_0 - [Au]_{\infty})^{2.0}} \right\}^{-0.50} + [Au]_{\infty}$$

- The model uses the leach particle size (P<sub>80</sub>) and mill feed grade [Au]<sub>HG</sub> to determine the unleachable gold content [Au]<sub>∞</sub>. The retention time (t) is a function of mill throughput rates (tpd) and slurry density (% solids w/w).
- The leach rate constant (k<sub>leach</sub>) was found to be a function of leach circuit operating temperature and leach cyanide concentration [NaCN].

$$k_{leach} = \left\{ \frac{[NaCN]_{actual}}{[NaCN]_{ave}} \right\} 2.84 \times 10^{33} e^{-20,870(1/T)}$$

- The CIP circuit solution tailings gold concentration is best estimated by the following 1<sup>st</sup> order rate equation, where [Au]<sub>L7</sub> is the gold concentration in the CIP feed solution.

$$[Au]_t = [Au]_{L7} e^{-k_{CIP} t}$$

- The CIP rate constant (k<sub>CIP</sub>) was found to be a function of CIP circuit operating temperature (T) and the carbon advance rate (AR) as follows:

$$k_{CIP} = \left\{ \frac{AR_{actual}}{AR_{ave}} \right\} 0.22 e^{-918(1/T)}$$

- The periodic processing of straight Fort Knox ore in 2004 allowed for validation of the gold leach and adsorption models that were developed primarily on pre-2001 data. Modeling the effect of processing True North ore can now be completed using the Fort Knox ore processing model as a baseline to isolate variances associated with ore types.
- A second paper in this series will focus on modeling the impact of slurry temperature on the cyanide destruction circuit at the Fort Knox mill.

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