

Application of Laboratory Stream Tube Testing to Economic Evaluation of Solution Mining

GL03958

J.W. Murphy, K.J. McGrew, and R.H. Jacobson

Introduction

Maximization of profit consistent with environmental protection is the principal goal of new applications development for any conventional or in situ mining technique. Efficient evaluation of all the parameters that contribute to mining costs and production hinges on proper design and evaluation of testing programs and data.

The program discussed uses several field and laboratory procedures to estimate ore deposit characteristics and optimize lixiviant compositions. Ore characteristics and lixiviant compositions are then used in a long path leaching test (stream tube test). Stream tube test data are analyzed by mathematical models with computer assistance to predict such wellfield rate parameters as target metal production, lixiviant consumption, and restoration. When these predicted rates are combined with market values for target metals, capital expenditures, prices of lixiviant chemicals, and other economic variables (labor costs, power rates, and licensing fees), an assessment of the relative feasibility of various proposed mining plans is possible. The flowsheet in Fig. 1 illustrates this process.

Field and Laboratory Procedures

In general terms, the procedures followed in the evaluation of an in situ leaching application aim at accomplishing:

- rapid leaching and maximum recovery of the target metal in a marketable form,
- low consumption of lixiviant chemicals,
- unquestionably satisfactory restoration of the mined aquifer, and
- minimization of capital and operating costs for the above through development of an optimum mine plan.

Keeping these goals in mind, the following minimum test program is generally recommended.

Geology

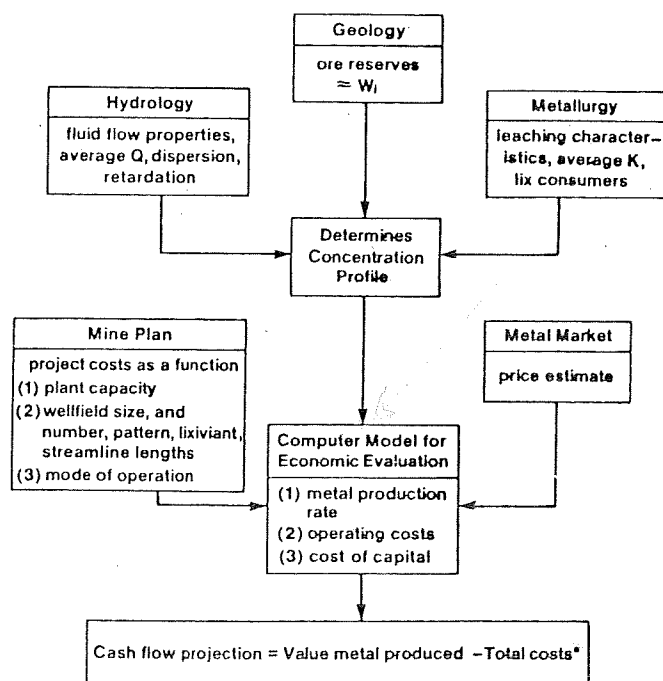
- Estimate of ore reserves and their variability.
- Average disequilibrium value for uranium deposits.
- Ore thickness, depth to ore, water level, degree of confinement, and consolidation.
- Characterization of quality and quantity of other ore deposit constituents (e.g. sulfide minerals, ion exchange parameters).

Hydrology

- Single well pump and injectivity test.
- Downhole vertical permeability test to compare flow rates of barren and mineralized formations.
- Groundwater quality as it may affect licensing, hydrometallurgy, and restoration.

Hydrometallurgy

- Flask or autoclave tests for optimization of lixiviant parameters and determination of specific reaction rate constants.
- Flask or autoclave tests for assessing amenability of lixiviant solutions with ore, consumption of lixiviant, stability of metal in solution contacting ore, and environmentally important species mobilized.
- A long-path leach test for modeling the behavior of the lixiviant solution flowing through a long mineralized streamline (stream tube testing).
- Metal recovery tests from lixiviant solutions (ion exchange, electrowinning, etc.).
- Lixiviant regeneration tests.
- Environmental restoration tests.



*Total cost includes all capital, chemicals, royalties, licensing, taxes, labor, energy, maintenance, exploration.

Fig. 1—Economic evaluation flowsheet

J.W. Murphy is senior consulting chemist, K.J. McGrew, member SME, is project manager and principal metallurgist, and R.H. Jacobson, member SME, is vice president for market development, all with In-Situ Inc., Laramie, WY. SME preprint 83-648. SME-AIME Fall Meeting, Salt Lake City, UT, Oct. 1983. Manuscript Dec. 1983. Discussion of this paper must be submitted, in duplicate, prior to July 31, 1984.

Discussion

The present discussion focuses primarily on the stream tube test, its execution, application, and benefits.

Goals and Uses

The specific goals of the stream tube test are to: measure the breakthrough characteristics of the target metal and the lixiviant; develop mathematical expressions (algorithms) describing the behavior of the target metal in the stream tube (concentration in terms of stream length and time or number of pore volumes); develop algorithms describing the behavior of the active components of the lixiviant in the stream tube; develop algorithms describing the behavior of various chemical species in the restoration phase of the test; and define the stoichiometry of lixiviant solution and gangue material interaction.

The stream tube simulates one streamline of many that could be considered to flow between two wells in an in situ mining operation. Computer synthesis of many streamlines into a mining production pattern is then possible using the algorithms developed from the test data. Synthesizing breakthrough times, peak concentrations, and production rates for the target metal from a number of streamlines by computer simulation gives some indication of expected mine production rates.

Figure 2 shows a wellfield with a number of streamlines of lixiviant flow between an injection well and a production well. Figure 3 shows, in general terms, the shape of the concentration profile of the target metal of one of these streamlines at the production well. This is basically the shape of the concentration profile at the effluent of the laboratory stream tube. Figure 4 depicts the expected production envelope for the convergence of many streamlines at the production well for a wellfield.

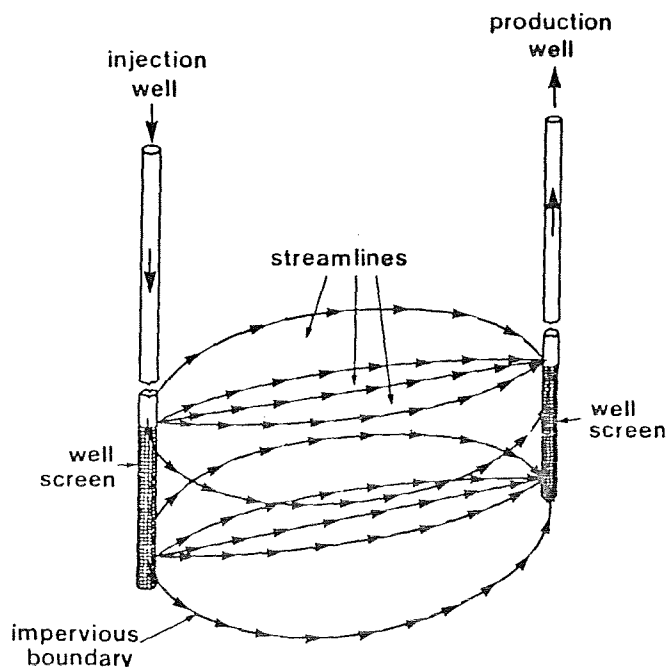


Fig. 2—Stream tube fluid flow between production and injection wells

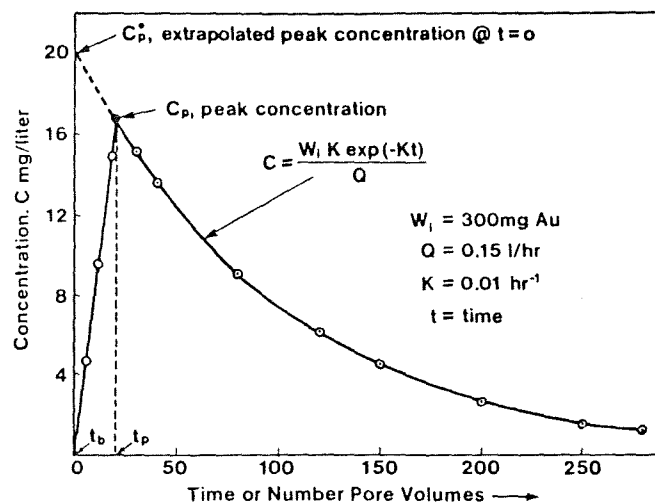


Fig. 3—Typical concentration profile

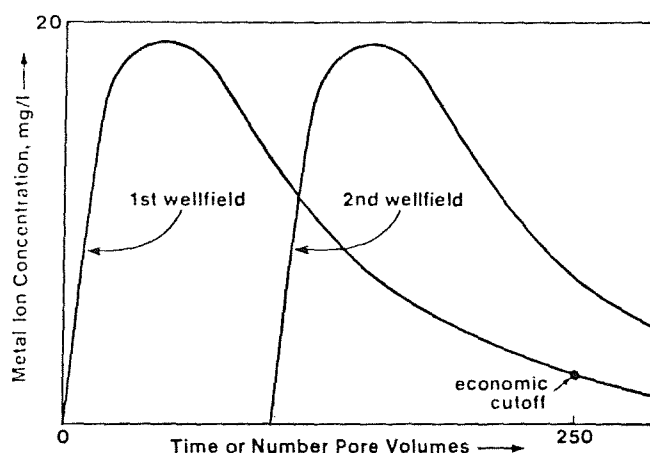


Fig. 4—Multiple stream tube concentration profile

Some estimate of chemical operating costs should be given by synthesizing breakthrough times and steady-state concentrations of active lixiviant components from a number of streamlines. Further, estimates of expected recoveries of lixiviant components and of length of time of hydrochemical restoration of the wellfield should be forthcoming from synthesis of decay rates of the various chemical species from different streamlines in the restoration phase of the operation.

With the information garnered from the stream tube test, a more efficient, economically productive mining plan can be formulated. Subsequently, the mining plan can be evaluated economically with the data acquired to assess the overall feasibility of the plan. These considerations are depicted in the flowsheet in Fig. 1.

Example of a Stream Tube Test

A laboratory setup for a stream tube test is shown schematically in Fig. 5. In actual practice, the test discussed here employed 20 plexiglass tubes, 50 mm OD \times 2 m (2 in. OD \times 6 ft) length, for a total 36 m (120 ft) of stream distance. The first tube was packed with quartz grains while the next 19 tubes were packed with a mixture of quartz grains and marcasite grains with 25 mm (1 in.) (about 0.018

g or 0.03 sq in.) of pure gold wire imbedded in the top 50 mm (2 in.) of each column. This yielded 35 m (114 ft) of simulated ore having a marcasitic sulfur content of 0.18%, a permeability of 11 darcies, a synthetic gold assay of about 8 g/t (0.15 oz per st), and a porosity of 30.5%. Lixiviant solution was pumped through the columns at about 3 mL/min (0.04 gal per min per sq ft). The volume of solution in the 19 saturated columns was 12.9 L (3.4 gal) (one pore volume). Total weight of gold was 334 mg (0.01 oz) and total original surface area was 340 mm² (13.4 sq in.) or 1000 mm²/g (0.002 sq in. per oz) specific surface area. Seventy-two hours were required to pump one volume through the 19 column stream tube. In this example, lixiviant solution was pumped for 11.4 pore volumes (820 hours); then the column was "restored" by pumping an additional six pore volumes of synthetic "groundwater." The lixiviant was a single component system with an active, oxidized form (L_O) and an inactive, reduced form (L_R) with a total concentration $L_T = L_O + L_R$ of about 20 mmolar. Initial pH of the influent lixiviant solution was between six and eight with an Eh of about 650 mv.

Samples were collected at the effluent every 0.1 pore volume and analyzed for gold, L_O , L_T , pH, Eh, iron, and sulfate. These results are plotted in Figs. 6, 7, and 8 with a plot of accumulated gold recovery. In addition, cross-sectional samples were taken periodically at the effluent end of each of the 19 columns of the stream tube. These samples were analyzed for gold concentration and L_O . Several of these samples are depicted in Fig. 9.

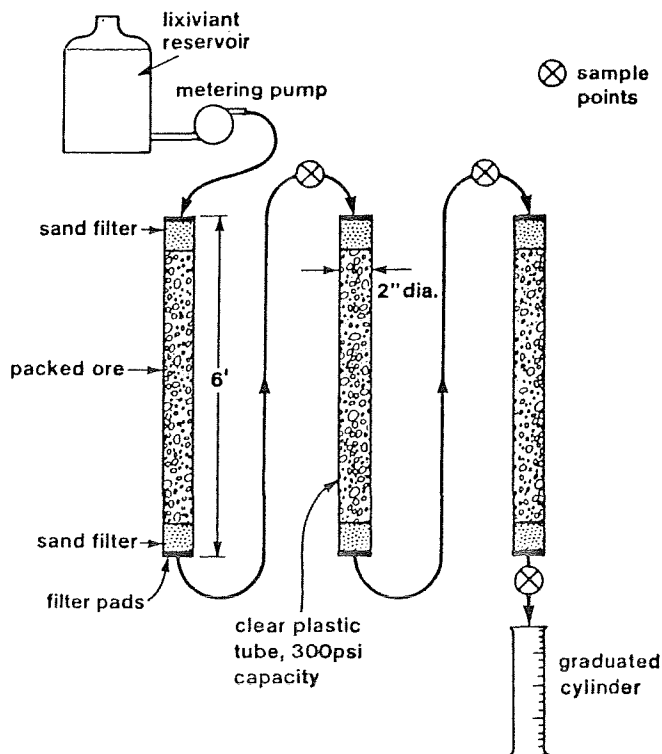


Fig. 5—Stream tube leach test apparatus

Results, Applications, Qualitative Expectations

Qualitatively, there are basically four lixiviant/ore/gold interactions that can take place in an ore deposit (Fig. 10). **Case 1:** The lixiviant dissolves the gold immediately with a rate constant of K , and neither gold nor lixiviant interacts with the rest of the ore body matrix. In this case, one would expect the gold concentration in the effluent to rise precipitously when the first of the solvent front breaks through, and then fall exponentially as more solution is discharged. Effluent value of L_O should be near the influent value.

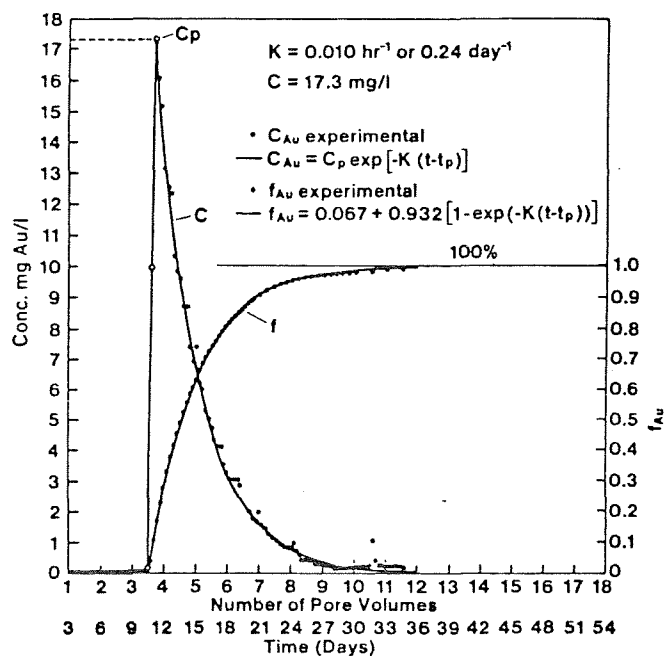


Fig. 6—Gold in stream tube effluent

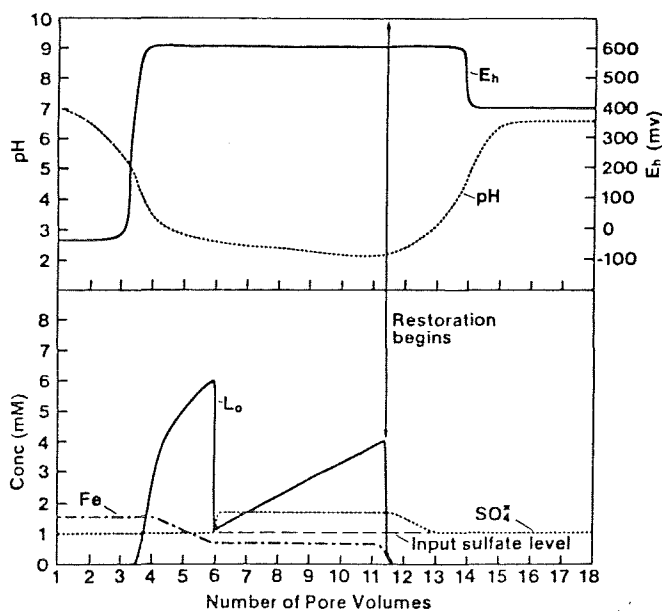


Fig. 7—Stream tube effluent concentrations for various products

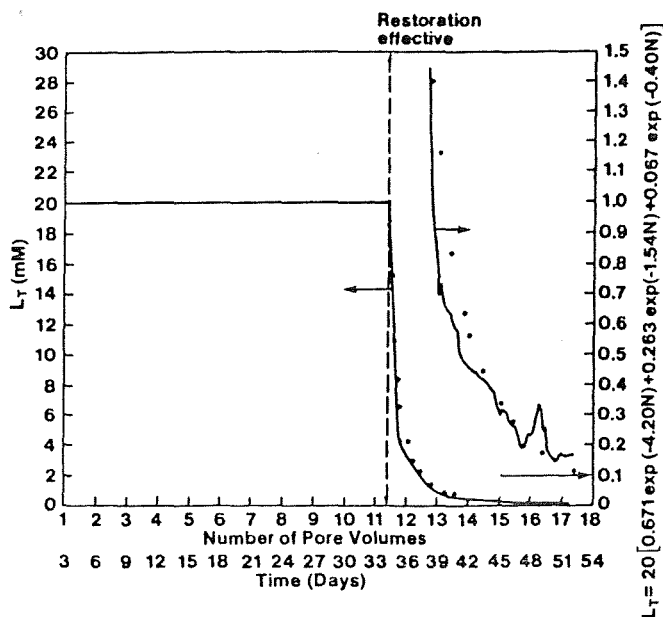


Fig. 8—Concentration of lixiviant component in stream tube effluent

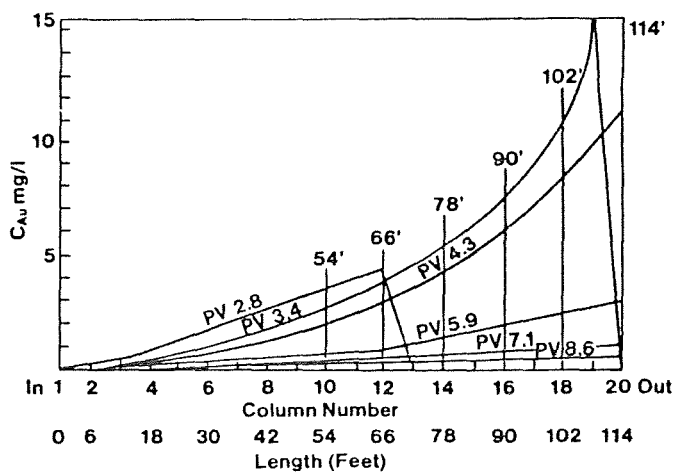


Fig. 9—Stream tube cross-section profiles

Case 2: The lixiviant dissolves the gold immediately with a rate constant of K , but an active component of the lixiviant is consumed by the ore material. This causes gold leaching to lag behind the advancing solvent front by a certain retardation factor, while the gold, which has been leached, remains in solution and is discharged in the effluent without retardation. In this case, it is expected that the gold concentration in the effluent will rise slowly when the solvent front first breaks through, attain a low maximum value at a time determined by the retardation factor of the lixiviant, and then fall off gradually from this peak. A steady state effluent value of L_0 less than the input value is attained after the lixiviant breaks through. The steady state value depends on the rate of interaction of L_0 and lixicides in the ore deposit.

Case 3: The lixiviant immediately leaches gold with a rate constant K , but is retarded by reaction with the ore material. The gold does not remain in solution in the absence of active lixiviant but reprecipitates in a form that redissolves when the retarded active lixiviant front catches

up. Thus, a buildup of gold will occur at the lixiviant front and no gold will be discharged at the effluent until the lixiviant breaks through. When the active front breaks through, however, a very high gold concentration will be attained rapidly but will then fall off exponentially from the peak. As in case 2, a steady state value of L_0 will be attained after lixiviant breakthrough, the magnitude of which depends on the rate of reaction with ore material.

Case 4: The lixiviant does not immediately attack the gold, but instead attacks the ore material. No gold goes into solution until all the consuming mineral in contact with the lixiviant is destroyed. Gold is then dissolved but subsequently reprecipitates at the lixiviant front. Here, there is a very long retardation time before a breakthrough of gold and lixiviant is achieved. It is expected that the peak gold concentration will be very high and will drop off exponentially. Effluent values of L_0 should be zero until breakthrough of lixiviant and then rapidly rise to near influent values.

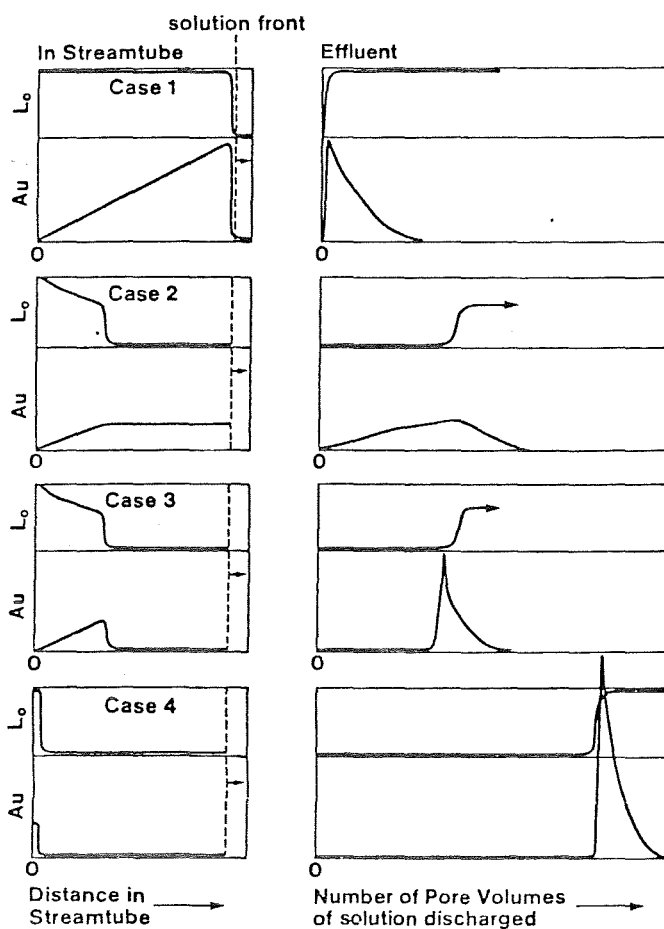


Fig. 10—Types of stream tube effluent profiles

The preceding discussion has been qualitative. Quantitative discussion is possible if the algorithms for describing the gold and lixiviant concentrations as a function of distance traveled in the stream tube and of time or number of pore volumes of solution passed are established. Such algorithms would permit computation of effluent gold concentrations for any streamline length at any time in terms of rate constant (K), total initial weight of gold in the streamline (W_i), solution flow rate (Q), and retardation factor (R_f).

With computer assistance, streamlines of various lengths could be averaged to yield an expected wellfield effluent profile for a given well pattern and known hydrologic streamline behavior. Even in the absence of descriptive algorithms, graphical estimates of gold concentrations as a function of time for various streamline lengths can be obtained from one stream tube test if a sufficient number of cross-section samples are taken to define clearly breakthrough times and peak gold concentrations. (In the present discussion, samples were not sufficient, but an estimate has been made for illustration.)

Figure 11 shows the gold values for various streamlines at the effluent for the cross-section data of Fig. 9. At any given stream length (or column number), a plot can be made of gold concentration versus time (or number of pore volumes) to get the corresponding graph of Fig. 11. All of these may then be averaged at any particular time to get the shape of the composite (wellfield) effluent profile (Fig. 12).

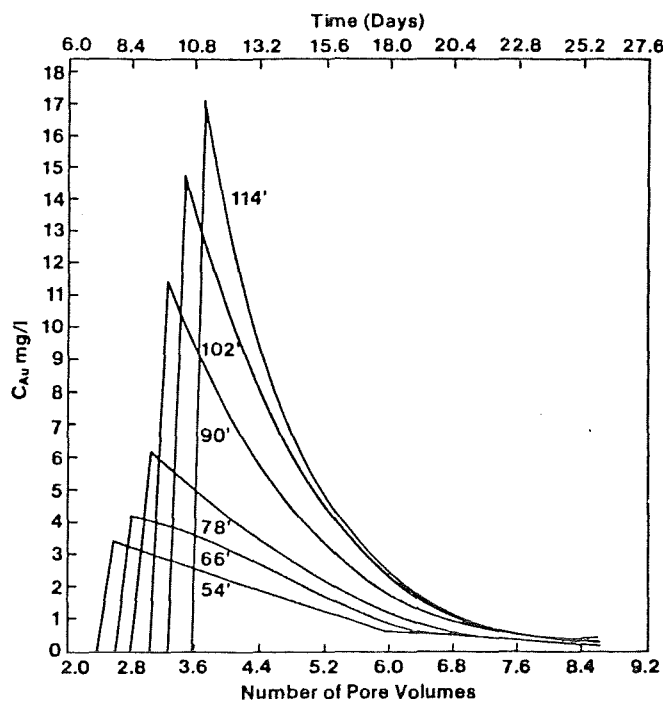


Fig. 11—Stream tube effluent profiles for various streamline lengths

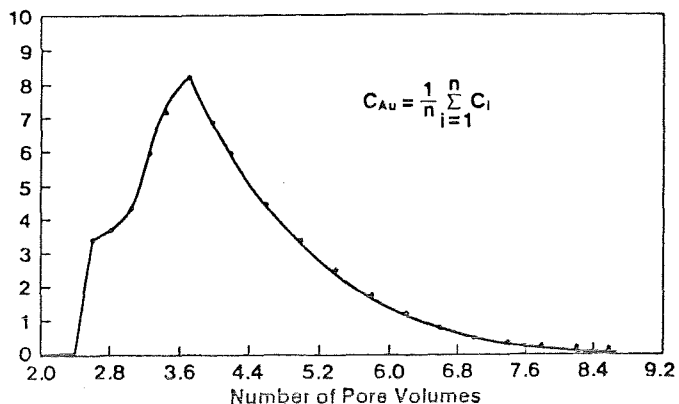


Fig. 12—Streamline effluent composite

Shape of the decay curve in the effluent. It is known that the fraction, f , of a metal removed from an ore body of initial metal weight, W_i , at any time, t , is frequently described by an exponential formula,

$$f = 1 - \exp(-Kt) , \quad (1)$$

where K is the apparent rate constant with units of reciprocal time, $[1/t]$ (Taylor and Whelan, 1942). This expression is valid if the rate of removal, R , of metal is proportional to the weight, W , of metal remaining in the ore body. Thus,

$$f = \frac{W_i - W}{W_i} \quad \text{or} \quad 1-f = \frac{W}{W_i} . \quad (\text{by definition}) \quad (2)$$

$$R = \frac{dW}{dt} = W_i \frac{d(1-f)}{dt} , \quad (\text{by definition}) \quad (3)$$

and

$$R = KW = W_i K (1-f) . \quad (\text{by theory}) \quad (4)$$

So,

$$W_i \frac{d(1-f)}{dt} = W_i K (1-f) , \quad (5)$$

or,

$$\frac{d(1-f)}{(1-f)} = K dt \quad (6)$$

Integrating the left hand side of equation (6) from $f = 0$ to f and the right hand side from the corresponding t values of 0 to t , yields,

$$\ln(1-f) = -Kt , \quad (7)$$

which rearranges to give equation (1).

Since concentration, C , can be thought of as the volume derivative of weight removed,

$$C = \frac{d(W_i - W)}{dV} , \quad (8)$$

proper differentiation of equation (1) with respect to volume of solution should yield an expression for the stream tube metal ion concentration. In the case of a lixiviant moving at a flow rate Q , the time derivative of volume is

$$Q = \frac{dV}{dt} . \quad (9)$$

Thus,

$$C = \frac{d(W_i - W)}{Q dt} = \frac{W_i}{Q} \frac{df}{dt} = \frac{W_i}{Q} \frac{d[1 - \exp(-Kt)]}{dt} , \quad (10)$$

or

$$C = \frac{KW_i}{Q} \exp(-Kt) \quad (11)$$

When $t = 0$, of course, C has its maximum value:

$$C_{\max} = \frac{KW_i}{Q} \quad (12)$$

Thus, it is apparent that the magnitude of the maximum solution concentration flowing from the ore body is directly proportional to K and W_i ; and inversely related to Q .

Stream tube profile. Figure 6 shows that the gold concentration and fraction of gold removed in the stream tube effluent are governed by equations similar to expressions (1) and (11). After the peak concentration of gold (C_p) is reached at time t_p , the concentration of gold drops at an exponential rate proportional to peak height, so that

$$C = C_p \exp[-K(t-t_p)] \quad (13)$$

The value of the fraction leached, f , is composed of two additive parts: before the peak, f_b , and after the peak, f_a . Before the peak, f_b is simply the area of the triangle (t_b , t_p , C_p) with unit fractions inserted appropriately. Thus,

$$f_b = \frac{C_p(V_p - V_b)}{2W_i} = \frac{C_p(N_p - N_b)V_p}{2W_i} = \frac{C_p Q(t_p - t_b)}{2W_i} \quad (14)$$

where V is volume of solution, N is number of pore volumes, V_p is the volume of one pore (12.9), subscript b refers to breakthrough, and subscript p refers to peak. After the peak, the value of f_a is given by

$$f_a = \frac{1}{W_i} \int_{V_p}^V C_p \exp[-K(t-t_p)] dV, \quad (15)$$

or since $dV = Qdt$,

$$f_a = \frac{QC_p}{W_i} \int_{t_p}^t \exp[-K(t-t_p)] dt, \quad (16)$$

and thus,

$$f_a = \frac{QC_p}{KW_i} [1 - \exp[-K(t-t_p)]] \quad (17)$$

The total fraction appearing after the peak is computed by setting $t = \infty$ in equation (15), resulting in,

$$f_a^\infty = \frac{QC_p}{KW_i} \quad (18)$$

For the gold leaching experiment discussed here, $C_p = 17.3$ mg/l, $Q = 18$ l/hr., $W_i = 334$ mg, and $K = 0.010$ hr⁻¹. Thus, $f_a^\infty = 0.932$. For equation (14), since $N_p - N_b = 0.2$, $f_b = 0.067$. Combining equations (12) and (17), it is seen that

$$f_a = \frac{C_p}{C_{\max}} [1 - \exp[-K(t-t_p)]] \quad (19)$$

where it is evident that $C_p/C_{\max} = 0.932$, differing from equation (1) by this factor. It is also seen that this factor, 0.932, is given by,

$$f_a^\infty = 1 - f_b = \frac{C_p Q(t_p - t_b)}{2W_i} \quad (20)$$

Computing K from log plots. In situ mine operators may use average daily values of Q and C to compute metal production values of f . A daily plot of $\ln(1-f)$ versus t will frequently yield a straight line graph that can readily be extrapolated to an economic cutoff and termination of mining. Plots of $\ln C$ versus t may also be used to predict at what time a new wellfield must be brought into production to maintain a high average metal ion concentration for the recovery plant feed. This type of assistance for mine planning can affect management estimates of fluid flow capacity for metal recovery, processing, the number and size of wellfields in simultaneous production, and restoration. Figure 13 shows plots of $\log C$ versus t and $\log(1-f)$ versus t for the effluent from this stream tube test. The value of K appears to be constant (0.010 hr⁻¹) over a good portion of the graph, and these data would be quite good for field application were they actual wellfield effluent data. However, two problems arise.

If recovery at $t = \infty$ is incomplete, $\log(1-f)$ versus t does not yield a straight line and no extrapolation can be made. This is seen in Fig. 14 where data are plotted for $f^\infty = 0.78$. Note, however, that $\log C$ versus t still yields a straight line so that extrapolation in the C - t framework is still viable. Further, a plot of $\log[1 - (f/f_{\max})]$ versus t , also in Fig. 14, does yield a straight line, where f_{\max} is the maximum fraction recovered at $t = \infty$.

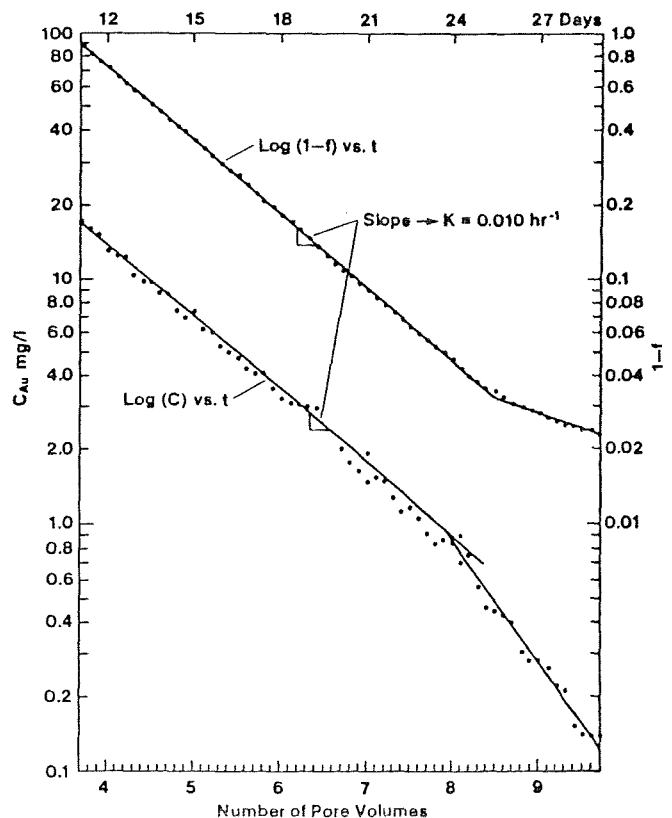


Fig. 13—Log-linear plots of fraction gold extracted and concentration gold in solution

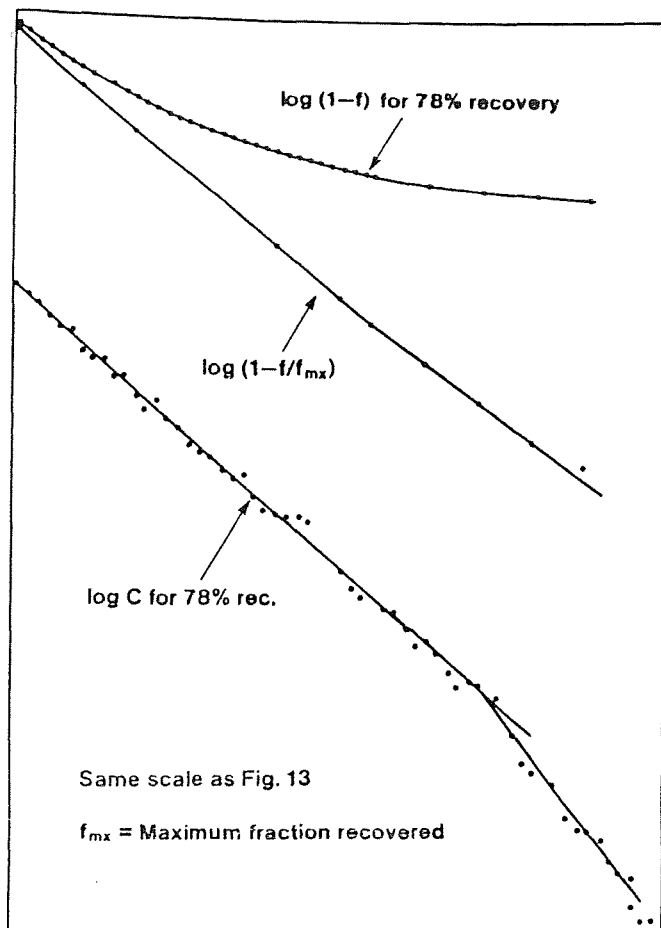


Fig. 14—Log-linear plots for incomplete recovery

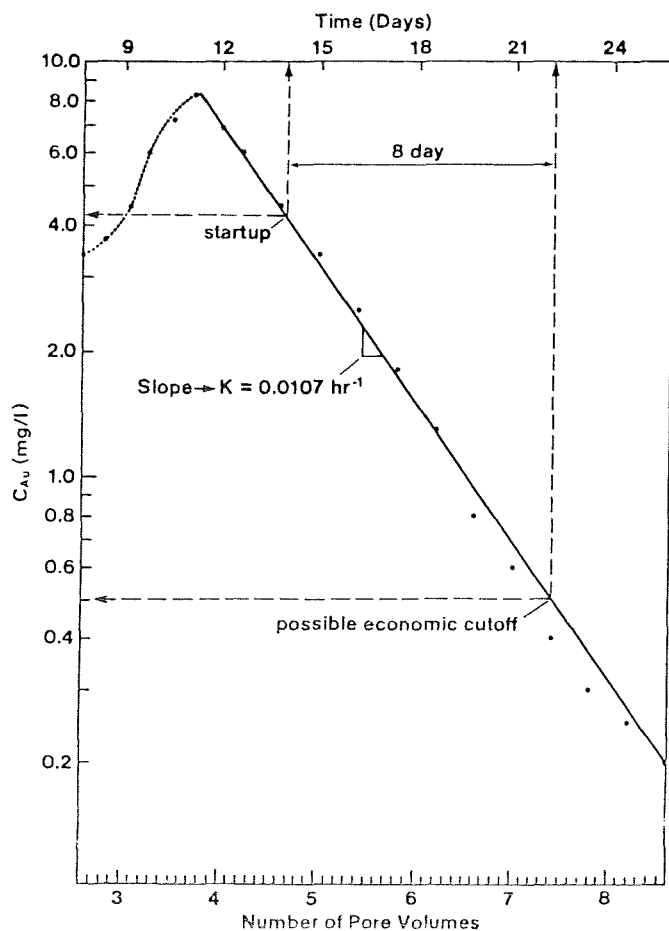


Fig. 15—Log C vs. t for stream tube composite

This example is for only one streamline. What if many streamlines converge? The mathematics do not give much hope of a single exponential function approximating a sum of many different exponential functions. In this case, however, when a plot was made of the composite curve from the cross-sectional stream tube data, a good match between the log C versus t type plot and the actual data was apparent (Fig. 15). This graph might be used in the following manner for a wellfield situation. After the peak is attained, concentrations of gold in the effluent are obtained at 12-hour intervals for a couple of days to get four or five points on the graph. A straight line is fit to these points and extrapolated to 0.5 ppm, the economic cutoff for recovery plant feed in this example. This point is reached at about 22 days. Since it takes about 8 days for the gold complex to break through in a new wellfield, the new field must start up before day 14 of the present operating wellfield in order for economic operation to continue.

Obviously, this kind of information is most useful before mining is begun; otherwise, the next wellfield will not be ready when it is needed to maintain plant feed levels above the cutoff grade.

Restoration

During mine restoration, it is necessary to have some idea of how long it takes to reduce the concentration of certain chemical species in the mined aquifer to acceptable environmental levels. The stream tube may also help in this area. Consider the behavior of L_T in the restoration phase of the stream tube (see the graph of L_T in Fig. 8). During mining, L_T concentration in the effluent was about 20 mmolar. Environmental requirements are such that the effluent concentration must be reduced to less than 0.1 mmolar. Groundwater is pumped through the wellfield and lixiviant chemicals are recovered on the surface to restore the aquifer to the environmentally acceptable limit. In Fig. 8a the concentration of L_T drops precipitously as restoration becomes effective at 11.4 pore volumes. At this point, it appears that the restoration is proceeding quite well. In fact, if one projects what will result based on a simple exponential decay formula,

$$L_T = L_{Tmax} \exp[-k_D t] \quad (21)$$

where k_D is a dilution constant, one would expect the formation to be clean very quickly, within a half pore volume. However, very soon the rate at which L_T drops decreases, and it becomes apparent that effective restoration will take longer than first anticipated. A new estimate of complete restoration time can be made that projects complete restoration by 1.5 pore volumes. Indeed, on the scale of Fig. 8a, it appears that the formation has been effectively restored by pore volume 12.9. However, analysis shows that a significant amount of L_T yet remains, and the graph of Fig. 8b, with a scale 100 times that of Fig. 8a, shows that L_T is still far above environmental acceptability and is decreasing sharply. In fact, it appears that the decay of L_T is best considered according to an expression like

$$L_T = L_{Tmax} \{ f_1 \exp(-k_1 t) + f_2 \exp(-k_2 t) + f_3 \exp(-k_3 t) + \dots \} \quad (22)$$

where the different terms represent different modes of occurrence of the particular chemical species in the formation (solution, ion exchange, etc.). The f_s are the

fractions of L_T in these various modes and the k 's are the different decay constants for the various modes where $k_1 < k_2 < k_3 < \dots$. With adequate stream tube data and restoration phase sampling at the cross-section sample points, each chemical species of environmental interest exiting the stream tube can be fitted to such a series and estimates made of appropriate restoration algorithms for a given streamline. A complete algorithm would include an equation similar to equation (22) where L_{Tmax} , f_n , and k_n were all functions of streamline length. With such an algorithm, it is possible to project restoration times and better estimate restoration costs.

Summary

The stream tube test can be a valuable tool for estimating the behavior of a lixiviant solution in a wellfield. The test provides a link between simple laboratory flask and autoclave tests and field tests. The various effluent concentration data for leaching and restoration can provide a clear understanding of the interaction of parameters controlling in situ mining.

The equations used here describing peak concentration of the target metal and the subsequent decay profile can be used with other algorithms yet to be developed to approximate recovery plant metal production as a function of time or number of pore volumes.

With the use of computer simulation techniques of various wellfield fluid flow patterns, coupled with cash flow projections, mining properties can be quickly and efficiently evaluated for potential mining as a function of metal prices and mining plans. ■

Acknowledgments

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Mercury Removal From Gold Cyanide Leach Solution

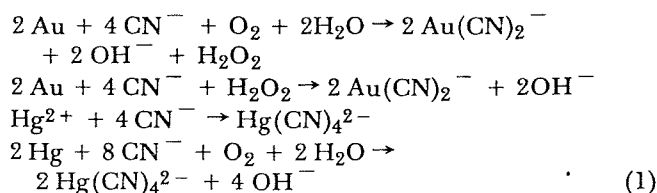
W.L. Staker, W.W. Simpson, and R.G. Sandberg

Abstract—The Bureau of Mines investigated selective extraction of Au and Ag from a low-grade Au ore containing Hg. Gold and silver were extracted from the ore in cyanide slurries, and Hg extraction was suppressed with sodium or calcium sulfide. Maximum Au extraction and minimum Hg extraction were obtained using solutions containing 17 kg NaCN/t of solution (0.34 lb NaCN/st). Increasing the cyanide concentration increased Hg extraction without increasing Au extraction. Mercury extraction from the ore was suppressed with 0.5-2.9 kg CaS/kg Hg (0.5-2.9 lb/lb) in the ore. Gold-to-mercury ratios of 100:1 to 400:1 were obtained in the leach solution, and on the activated carbon in a CIP circuit.

Introduction

During the past few years, several low-grade Au ore deposits containing Hg have been developed and are being processed by cyanidation to recover precious metals. These ores usually have less than 15 ppm Hg content. During cyanidation, 10-30% of the Hg is extracted along with Au and Ag. Gold, silver, and mercury are adsorbed from the leach solution by activated carbon in a carbon-in-pulp (CIP) circuit. The metals are stripped from carbon with hot solutions of sodium hydroxide-sodium cyanide or alcohol-sodium hydroxide-sodium cyanide. The metals are recovered from the strip solution by electrolysis onto steel wool

cathodes (Laxen, 1979). Cathodes are retorted under vacuum at 650-700°C (1202-1292°F) to remove Hg prior to smelting Au to Dore bars (Thorndycraft, 1982). Generally, small amounts of Hg extracted from the ore are more of a nuisance than an economic asset and require additional process steps for Hg separation from Au and Ag. In addition, Hg vapor may cause health hazards in the electro-winning, the retorting, and the carbon reactivation areas. Reactions representing Au and Hg extraction with cyanide (Potter, 1978) are:



W.L. Staker, W.W. Simpson, and R.G. Sandberg are with the Bureau of Mines' Salt Lake City Research Center, Salt Lake City, UT. SME preprint 83-654, SME Fall Meeting, Salt Lake City, UT, Oct. 1983. Discussion of this paper must be submitted, in duplicate, prior to July 31, 1984.

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