Use of a Chemical Transport Code for the Prediction of Gold Heap Leach Production

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INTRODUCTION

Itasca Denver, Inc., (Itasca) in conjunction with Newmont Mining Corporation (NMC) developed a numerical model to estimate gold (Au) production from NMC's heap-leach operations. A current practice of prediction of cyanide gold (AuCN) recovery at NMC is based on spreadsheet models (Excel®) that are unique for each operation. NMC has found that the tool is very useful for short- and long-term predictions of Au production; however, the methodology is limited for quantitatively assessing mechanisms for improvement and optimization of Au recovery. Hydrodynamic modeling is an alternative to the existing practice of prediction, and it is a complimentary addition to the existing predictive techniques.

METHODOLOGY

Selection of A Numerical Code for Heap-Leach Modeling

Modeling of the leaching and transport of Au in heap-leach pads is still considered as applied research. A literature search yielded a few examples of modeling fluid flow and Au transport in leach piles. There are a limited number of codes, commercially or publicly available, that can simulate chemical transport in the vadose zone (the zone that is located between the land surface and the top of the water table [Sterrett 2007]; flow conditions similar to a heap-leach pad). Also, there are no non-proprietary codes that might be used directly to predict AuCN recovery from heap-leach pads. It was clear that successful implementation of hydrodynamic modeling of heap-leach practices would require modification of an existing code. The main issue in heap-leach modeling is the ability to handle the interaction between Au in the solid phase and in the liquid phase. The selected code must simulate unsaturated flow and related mass-transport with interaction between lixiviant and solid phase (ore with Au content) when a second component (barren solution) appears in the system.

Only one publicly available code, *MOFAT* (Katyal et al. 1991), was found to be capable of satisfying the issue of the interaction of the various phases discussed above. *MOFAT* is capable of incorporating the interactions between the solid phase (assumed to be oil in *MOFAT*) and water due to its mathematical capabilities. *MOFAT* was developed and

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used primarily to model multi-phase flow (water, oil, and gas) in the un-saturated zone in two dimensions; however, the mathematical structure of the code allows it to be applied to flow and transport problems in the vadose zone by eliminating oil and gas as mobile phases. A significant reason that Itasca selected this code is due to Itasca's previous experience working with the code and the fact that the mathematics of the code can be used to simulate gold recovery over time. An additional advantage of *MOFAT* is its capability to explicitly assign the content of the gold in the ore and calculate (simulate) Au depletion. Lastly, the code is publicly available; one of NMC's requirements was that the code should not be a proprietary code.

Given the dimensions of the heap-leach pads and that the flow of lixivian is essentially vertical through the heap pads (under the influence of gravity) the analysis of fluid flow and Au transport can be performed as two-dimensional (2-D) flow instead of a complex 3-D model. A 2-D analysis is also supported by the fact that lateral flows occur at the bottom of the pad.

Adaptation of the Code for Heap-Leach Analysis

Several modifications to the code were performed before the code could be used for heap-leach simulations. The modifications are summarized below:

1) Decoupled the oil/water flow equations so that pressure head, saturation and mass-balance of water do not depend on oil content (Au content in the revised code)

2) Modified to solve the problem of activation of "low" Au concentrations in the ore. The original *MOFAT* code assumes a limitation on the interaction (dissolution) between water and oil depending on "oil" saturation (oil is "Au" in the modified code)

3) Incorporated the ability to calculate mass balances in the system

4) Replaced the original flow and transport solvers (direct Gaussian method) with new, robust ones (direct and two iterative matrix solvers). Now, the speed and convergence of the flow modeling is significantly improved. The stability of the solution also improved

The revised *MOFAT* code is now entitled Gold Heap Leach Simulator (*GHLS*). As part of the new code, a user-friendly graphical user interface (GUI) was developed. The original *MOFAT* code was written in *FORTRAN* with difficult formats for input parameters. Itasca developed the GUI in a standard *Windows*™-based format. Such a user-friendly GUI allows for a relatively easy way to create complex models. Specific features of the GUI are:

1) Adoption of different units for Au contents and automatic conversion between units used (grams/ton, troy ounces/short ton, volumetric content)

2) Use of initial water conditions in terms of moisture content, degree of saturation and pressure head with automatic conversion between units

3) Incorporation of the ability to have multiple lifts and pads constructed over time. The model was adapted such that the results of one lift are stored and used in subsequent model runs when additional lifts are added. In summary, the results of modeling of the previous lifts will be read as initial conditions for the next lift.

4) Visualization of the results of the modeling in terms of saturation, pressure head, Au contents in the ores and in the pregnant solution, and lixiviant penetration into the ores

5) Re-calculation of the predicted AuCN recovery in terms of monthly production depending on initial date of rinsing

6) Export of output data (saturation, pressure head, lixiviant consumption, and Au in pregnant solution) in ASCII file format for a discrete time so the data can be used to create high-quality plots of cross sections in commercially available and popular software such as *SURFER*™ and *TECHPLOT*™*.*

HEAP-LEACH PAD MODELING (CROSS-SECTIONAL MODELING)

The first type of problem that the code was applied to is an application for a standard heap-leach operation where the lixiviant is applied on the surface of the lift and the flow of the lixiviant is strictly under the influence of gravity. The code was also applied to an axisymmetric problem; however, this application is not described in this paper. The initial cross-sectional model, a representation of cells 6 through 11, was applied to North Area Leach Expansion 7 (NAL-7)—where production has been ongoing since July 2007. The thickness of the pad that is simulated is dependent on the variability of the properties of the ore. Figure 1 shows a top view of the pad and the slices. The pad is located at NMC's North Area Leach facility that is located in northeastern Nevada (USA). The relatively short history of this expansion and availability of the records on rinsing schedules were of benefit to setting up the initial model for this pad. Also, numerous data from standard column tests on AuCN recovery were available to calibrate the *GHLS* model.

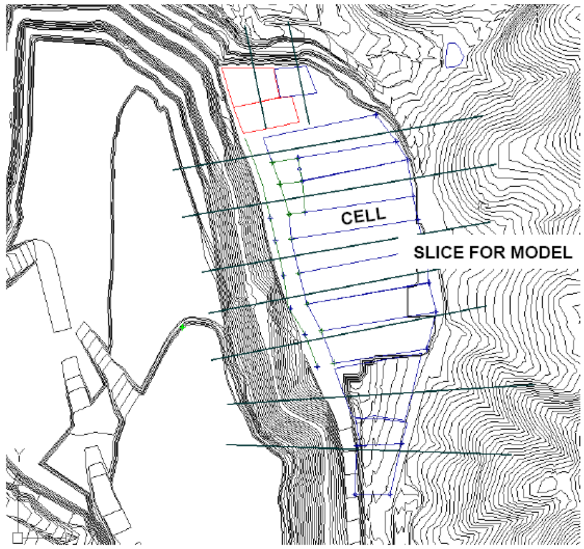


FIGURE 1. Selection of Slices for NAL-7 Heap-Leach Pad

Initial data supplied by NMC included gold concentrations, lixiviant application rates, and gold production rates. Laboratory samples for gold content and moisture contents were used for assigning different hydraulic zones in the model.

A schematic of the model grid and the steps for the modeling are represented in Figure 2. In a cross-sectional view of the pad the current and potential lifts are discretized into cells, and different hydraulic properties were assigned (Figure 2b) based upon geologic descriptions and moisture contents. The third part of the modeling assigned gold concentrations and moisture contents to the various units based upon laboratory analyses of ore samples from the pit (Figure 2c). Once the gold concentrations have been assigned, then the leaching/rinsing processes with a surface application (Figure 2d) were simulated.

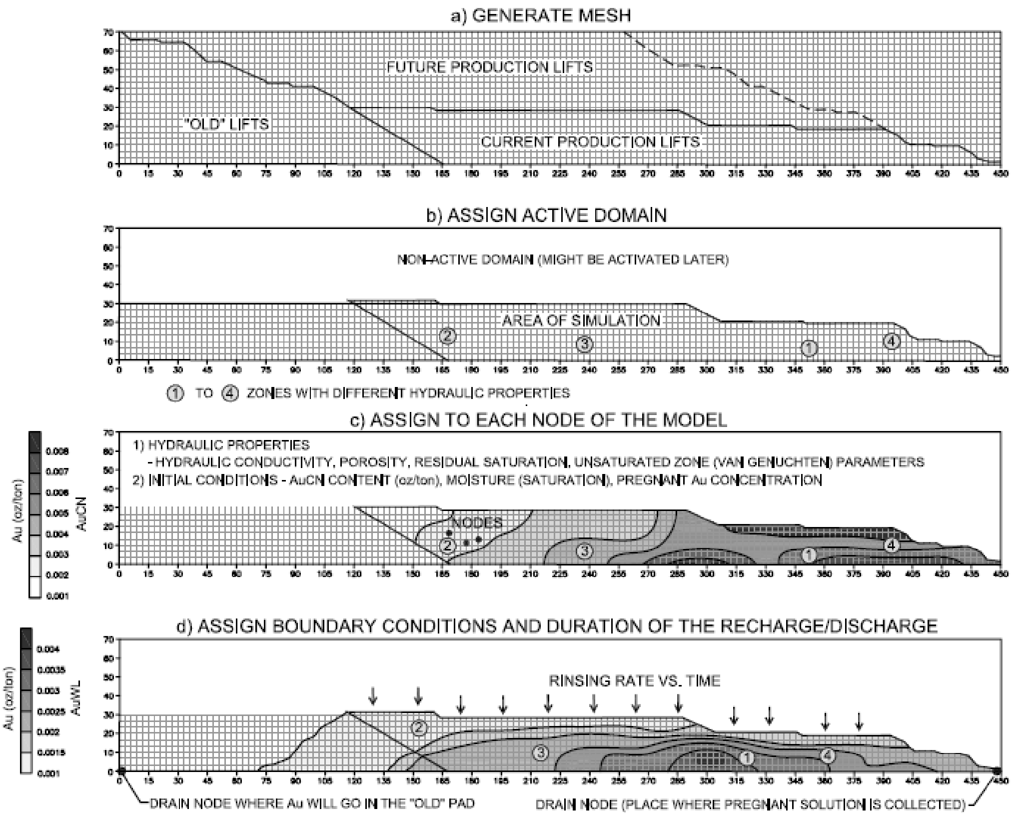


FIGURE 2. Schematic of Building and Running the Model

In the column tests, a delay in AuCN recovery was observed. This delay was simulated in the pad model by the use of a delay factor. In the field of contaminant hydrogeology, a delay in the movement of the chemical (in this case Au) relative to the movement of the fluid is termed “retardation.” Itasca found that the retardation of gold is proportional to the concentration of organic material within the geologic materials, primarily carbonaceous limestone/dolomites. The concept of a retardation factor incorporates several factors, in one way or another, which complicate AuCN recovery such as chemo/physical sorption and cyanide consumption by the ore. It was observed that the organic carbon content is an important parameter to calculate this retardation factor.

Figure 3 illustrates the correlation between organic carbon and the retardation factor for the ores in NAL-7. The numbers on the chart represent the numbers for the column tests. A reasonable average value for a retardation number is approximately 2.5. This means that the velocity of Au is 2.5 times slower than the velocity of the fluid.

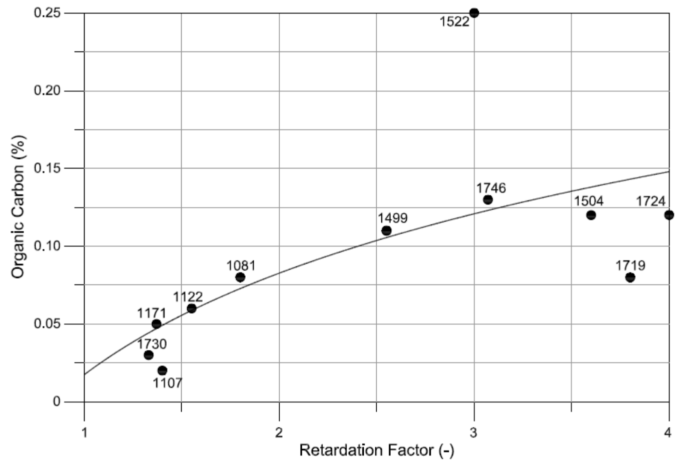


FIGURE 3. Dependence of Retardation Factor on Carbon Content (numerical interpretation of column tests)

A key parameter for the modeling is the hydraulic conductivity of the various ores. This parameter has not been determined for the ores in the pad except in column leach tests. Based on multiple runs of the model assuming the given application sprinkling rate (0.20 L/min/m^2 [005 gpm/ft^2]) and duration of application, the range of the hydraulic conductivities that are applicable for NAL-7 is between 50 to 70 m/day (164 to 230 ft/day). Lowering the hydraulic conductivity will lead to the development of a water table within the pad above the surface of the lifts.

The bulk porosity of the ore materials was calculated based on data of placed tons and volumes of the lifts. The calculated porosity is 0.29.

Variable Au contents were assigned in the model for the different lifts based on the data of placed tons and gold contents.

Critical information for the modeling is the maximum possible AuCN recovery for the specific types of ores. Itasca found, based on data from 36 column tests performed on NAL-7 materials, that AuCN recovery is in the range of 40 to 95% of AuCN content. Based upon field data, AuCN recovery for NAL-7 is approximately 74%; whereas, column test data recoverability is up to 95% (Figure 4).

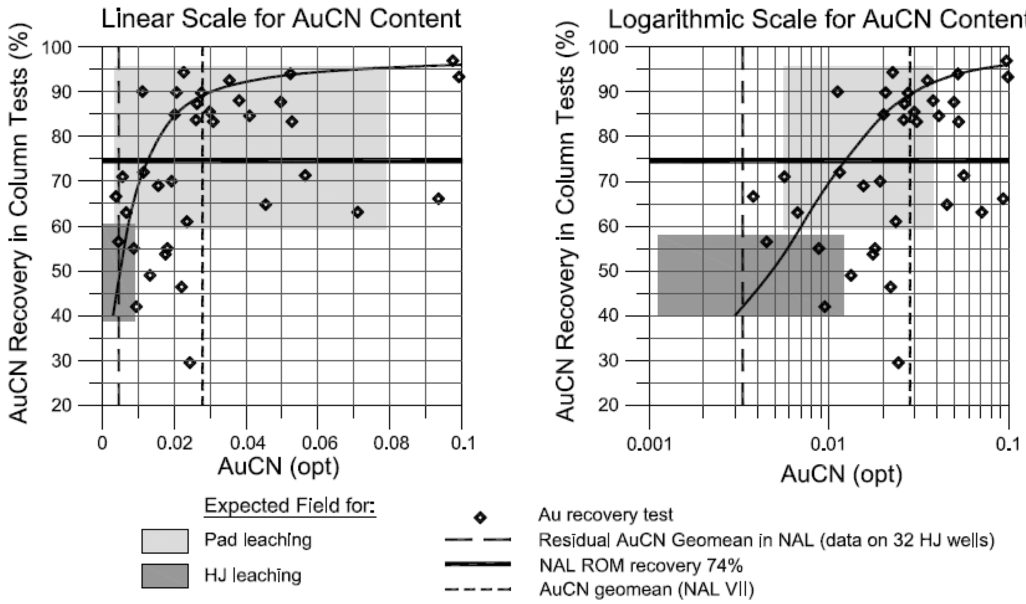


FIGURE 4. AuCN Recoverability vs. AuCN Content (based on column tests)

A value of 90% recoverability was used in the modeling as the highest potential for AuCN recovery. A lower number may result from the modeling due to the effective area of lixiviant penetration and trapping of the pregnant solution in the area of the low water saturation upon completion of the rinsing.

Itasca constructed a model of NAL-7 that included seven lifts and simulated operations of the pad from 2007 through 2019. As part of the simulation, estimates were made of the amount of AuCN extracted, the amount of AuCN that migrates to adjacent pads, and the amount of AuCN pregnant solution that remains within the pad

Results of Pad Modeling

The results of Phase 1 modeling of the pads show that the AuCN collected at drain pipes will be determined by the distance to the point of the discharge, location of the cell within the pad, the height of the pad, and the hydraulic properties of the ore materials. Figure 5 shows the results of the predictive simulation of monthly Au production for Lifts 1 through 7. The blanks between the columns represent the times that the pads are constructed. As noted in this figure the higher the pad, the less Au is recovered. Part of this is due to the long migration time through the pad.

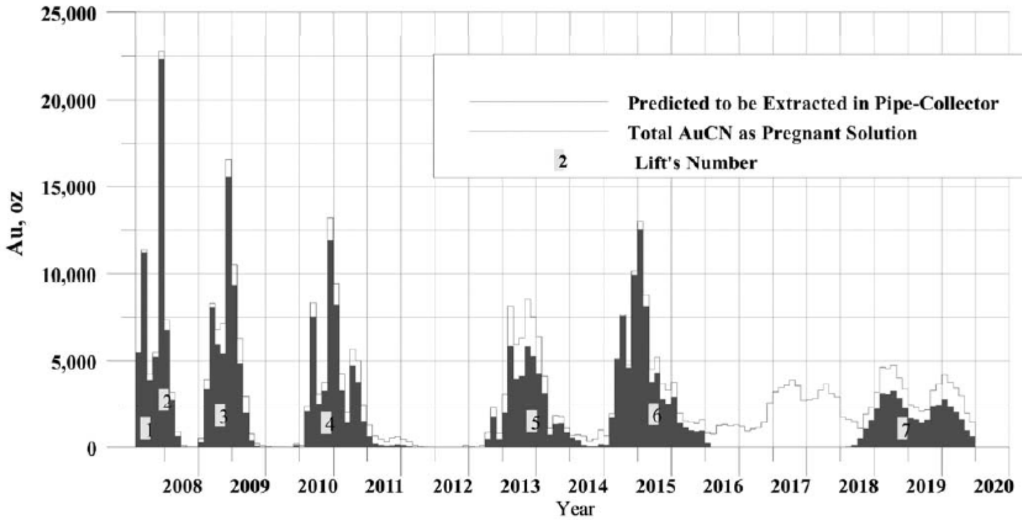


FIGURE 5. Results of Predictive Simulations of Monthly Au Production for Lifts 1 through 7 (composite model for cells 6 through 11, NAL-VII)

It was found that up to 30% of the pregnant solution will go into adjacent, older materials rather than be discharged directly into the collector pipes. Also, approximately 25% of all leached Au during the latest rinsing phase (Lift 7) might be left within the pad as pregnant solution. In summary, the recovery of Au is a function of the number of pore volumes of lixiviant that pass through the pad. Higher lifts will require longer durations of rinsing.

Use of Code to Evaluate Sensitivity of Input Parameter

An important analysis for assessing gold production is the knowledge of the amount of time from the initiation of leaching to actual gold production. Itasca was of the opinion that the delay time should depend on the type of ore, leach application rates, and the heights of lifts. The parameters that probably have the most influence on the rate of gold production are: value of hydraulic conductivity, initial moisture content, and organic carbon content. The sensitivity of these parameters on predicting gold production was simulated by the code. Several hypothetical scenarios assuming heights, leach application rates, and hydraulic conductivities that are found in the heaps at the Gold Quarry mine include two different ore types; a clayey material and a coarser material. In addition, the number of lifts was also varied.

Itasca produced a table of hypothetical leaching scenarios and Table 1 shows the 12 different scenarios that were simulated. This table shows that the value for hydraulic conductivity varied from 0.00006 m/s to 0.03 m/s (0.0002 feet per second (ft/s) to 0.1 ft/s). The range of these values was obtained from column test studies that were conducted by Newmont.

Table 1. Hypothetical Scenarios to Assess Lag Time in Gold Production with Assumed Parameters

Scenario Number	Hydraulic Conductivity (m/s)	Application Rate (L/s/m^2)	Porosity	Water Saturation	Organic Carbon Content (%)	Equilibrium Coefficient[1]	Lift Height (m)	# of Lifts
1	0.00006 (0.0002)	0.003	0.34	0.35	0.05	0.116	10 (30)	1
2	0.00006 (0.0002)	0.003	0.34	0.35	0.05	0.116	10 (30)	2
3	0.0003 (0.001)	0.005	0.32	0.33	0.05	0.109	10 (30)	1
4	0.0003 (0.001)	0.005	0.32	0.33	0.05	0.109	10 (30)	2
5	0.0003 (0.001)	0.005	0.32	0.33	0.05	0.109	10 (30)	3
6	0.003 (0.01)	0.005	0.29	0.3	0	0	10 (30)	1
7	0.003 (0.01)	0.005	0.29	0.3	0	0	10 (30)	2
8	0.003 (0.01)	0.005	0.29	0.3	0.1	0.406	10 (30)	1
9	0.003 (0.01)	0.005	0.29	0.3	0.1	0.406	10 (30)	2
10	0.03 (0.1)	0.005	0.27	0.28	0	0	10 (30)	1
11	0.03 (0.1)	0.005	0.27	0.28	0	0	10 (30)	2
12	0.03 (0.1)	0.005	0.27	0.28	0	0	10 (30)	3

Note: The assumed initial gold content for all runs will be 0.03 oz/ton
Numbers in parentheses are in US Customary Units
[1]Equilibrium coefficient = (Retardation Factor - 1) * porosity

The application rate was also varied. The rate was either 0.12 L/min/m^2 (0.003 gpm/ft^2) or 0.2 L/min/m^2 (0.005 gpm/ft^2). The lower application rate was used when the ore was judged to be of low hydraulic conductivity suggesting that the ore contained a higher percentage of clay.

The values of initial porosity and water saturations were also varied based upon variation in ore properties. Clayey ores were judged to have higher porosities and water saturations.

The organic carbon content and equilibrium coefficient are related through the retardation factor. The retardation factor is a comparison of the velocity of the leaching solution to the velocity of gold. Itasca found that the higher the organic carbon content in the ore, the slower the transport of gold, as previously discussed. From the retardation factor an equilibrium coefficient was calculated as shown in Table 1. The average bulk density of the ore was assumed to be approximately 1954 Kg/m^3 (122 lbs/ft^3).

Figure 6 shows a cross section of the model domain with up to three lifts being modeled. For each lift, the left side of the lift was considered to be an older portion of the lift and contained lesser amounts of gold. Figure 6 also shows the assumed gold concentrations for each portion of the lifts. The older portions of the heap-leach pile were assumed to contain 0.0001gm/kg (0.003 oz/ton) of gold where fresher ore contains 0.001 gm/kg (0.03 oz/ton) of gold. While this situation is not quite analogous to actual field operations, for the given hypothetical scenarios this distribution of gold per lift is not unreasonable and is analogous to new heap pads being added laterally to existing pads.

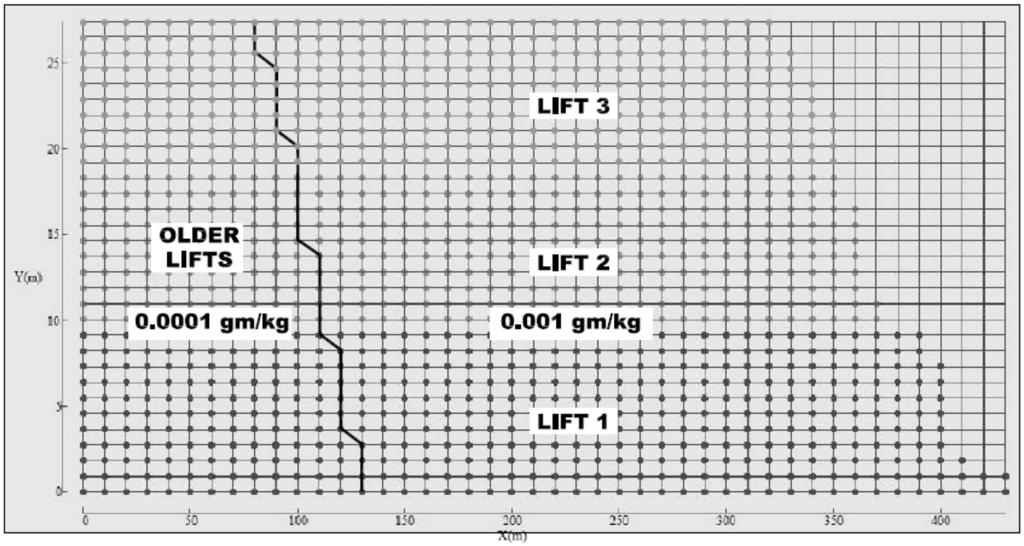


FIGURE 6. Construction of Model

Table 2 shows the initial gold contents in each of the lifts. The amounts of gold are listed in grams and ounces. As noted in the table, the amount of gold in Lift 2 includes the amount in the actual lift plus the amount still remaining in Lift 1. This concept is also applicable to Lift 3. In all cases, the width of the heap-leach pad is assumed to be about 1 m (3 ft).

Table 2. Initial Gold Contents in Lifts

	Lift 1	Lift 2	Lift 3
Initial gold content (g)	5,350	4,634	4,510
Initial gold content (oz)	172	149	145

Notes: Gold content of Lift 2 includes gold left in Lift 1 after leaching of Lift 1
Gold content of Lift 3 includes gold left in Lifts 1 and Lift 2 after leaching of Lift 2

Table 3 is a history of operational times for leaching. In the case of Lift 1, the pad is leached for 60 days with 70 days of inactivity. During the time of inactivity Lift 2 is constructed. As shown in the table, leaching and times for inactivity increase for Lifts 2 and 3.

Table 3. Operational Times for Various Lifts

	Lift 1 (Days)		Lift 2 (Days)		Lift 3 (Days)	
ON (leaching)	60		90		120	
OFF (draining)		70		90		90

Note: There is no time assumed for construction of next lift

RESULTS OF SENSITIVITY SIMULATIONS

Figures 7 through 11 show the results of the simulations for the various scenarios. Scenarios 1 and 2 were grouped as they have the same ore properties. Scenario 2 simulates the gold production from Lift 2 after Lift 1 has been leached (Scenario 1). This same grouping of scenarios is the basis for the other figures. The red vertical lines shown in the figures indicate the beginning of leaching for the next lift. In the case of Scenario 2 (Figure 7), the leaching of Lift 2 begins 130 days after the beginning of the simulation. The "jagged" nature of the curves shown in Figure 7b is probably due to numerical oscillations within the computations and reflects the fluctuation around the actual transport of gold. As noted in Figure 7, significant gold production (defined as 31 gm [1 oz] per day) begins approximately 19 days after the beginning of leaching and peaks approximately 43 days after leaching.

When the second lift is leached, significant production (>31 gm [>1 oz] per day) starts around 173 days or 43 days after the beginning of leaching of Lift 2. The peak production rate for the second lift (Scenario 2) is less than the first lift (87 versus 93 gm/day [2.8 versus 3 oz/day]); however, total production is only slightly less (3,577 versus 3,888 gm [115 versus 125 oz]). The lower production is due to the fact that there is less gold in the second lift.

Figure 8 shows the influence of lower porosities, water saturation, higher hydraulic conductivities, and leaching rates. Figure 8 shows an increased gold production in terms of cumulative production (8a) and daily production (8b). The different colored curves for Scenario 3 were to investigate the influence of the parameter α (one of the van Genuchten parameters) on gold production. As observed in Figure 8, there is little difference if the value of α is 1, 2 or 3. The remaining simulations assume a value of 3.

Figure 8 shows that there is lower total gold production for three lifts. The amount of gold recovered declines with an increase in the number of lifts. This is due to less gold in the third lift. Additional leaching would eventually remove this gold. Peak gold production for Scenario 3 occurs approximately 26 days after the beginning of leaching. The time to peak production increases with increasing the number of lifts. Figure 8 shows the efficacy of building fewer lifts or having liners between the lifts.

The influence of retardation of gold is shown in Figures 9 and 10. Scenarios 6 and 7 assume that there is no retardation of gold in the heap-leach pile; whereas, Scenarios 8 and 9 assume a significant percentage of organic carbon in the ore. Figures 9a and 10a show that the cumulative gold productions are about the same; however, the time to reach 7,776 gm (250 oz) has increased as shown in the two figures. Peak gold production in terms of gm/day is higher in the case of Scenarios 6 and 7 than Scenarios 8 and 9. It should be noted that the same amount of gold is "flushed" from the piles as discussed above. Without retardation, the gold is leached more rapidly from the lifts.

Scenarios 10 through 12 show the influence of high hydraulic conductivity and no retardation. As noted in Figure 11b, the peak gold production occurs within six days of leaching. Figure 11 also shows that the production rate increases for the third lift but that total production is less for the third lift (approximately 3,110 gm [100 oz]) than for the second lift (approximately 3,421 gm [110 oz]).

Table 4 shows the times to reach gold production rates of 16 gm (0.5 oz) per day and 31 gm (1 oz) per day as well as the maximum production rate and the time to achieve it.

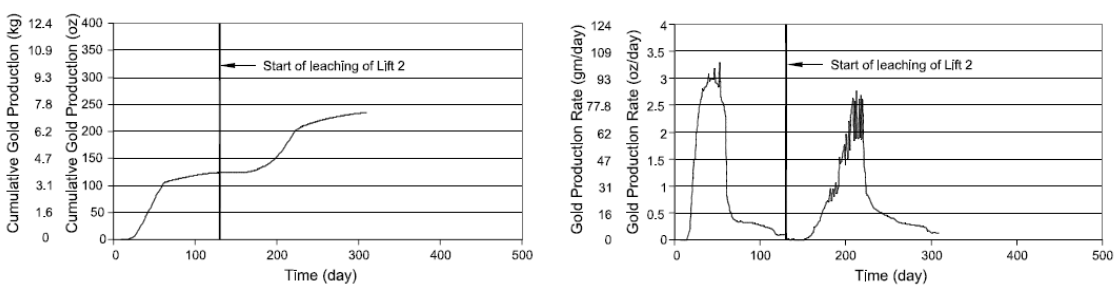
As noted in this table, the maximum time to reach the peak production rate for a single lift is 43 days (Scenario 1). For the situation where there are two lifts, the maximum time is 82 days (Scenario 2).

Table 4. Times for Production

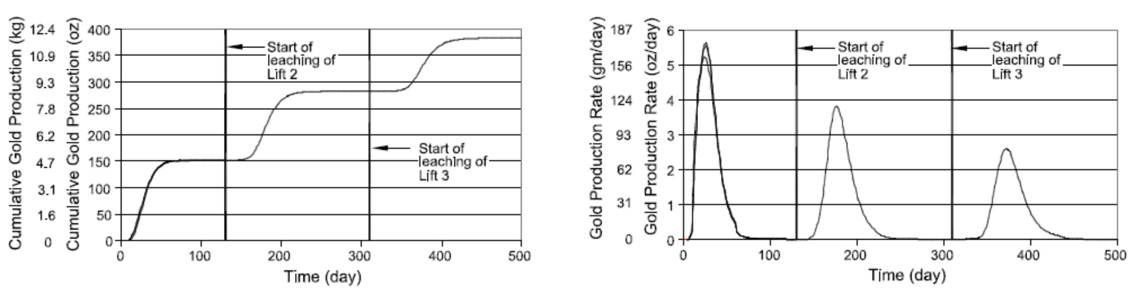
Scenario	Time to Reach 16 gm/day (0.5 oz/day) (days)	Time to Reach 31 gm/day (1 oz/day) (days)	Time to Reach Maximum Rate (days)	Maximum Rate (gm/day / (oz/day))
1	19	21	43	93 / (3)
2	43	62	82	87 / (2.8)
3	10	11	26	174 / (5.6)
4	24	28	46	118 / (3.8)
5	41	46	63	81 / (2.6)
6	4	4.5	12	289 / (9.3)
7	7	8	15	227 / (7.3)
8	9	10	18	168 / (5.4)
9	17	23	39	115 / (3.7)
10	1	1.5	6	541 / (17.4)
11	6	7	14	236 / (7.6)
12	4	7	12	295 / (9.5)

Note: Times shown in table are calculated from start of leaching of that particular lift.

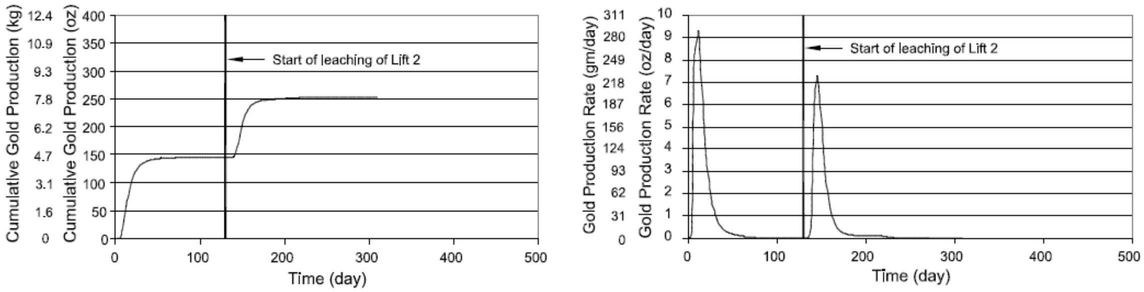
The primary difference between scenario combinations 6 and 7, and 10 and 11 is that the hydraulic conductivity for Scenarios 6 and 7 is ten times less than that for Scenarios 10 and 11. However, the times to reach maximum production for a single lift are 12 days (Scenario 6) versus 6 days (Scenario 10). For two lifts, the times for peak production are 15 days (Scenario 7) versus 14 days (Scenario 11). The information contained in this table suggests that when the one has a certain elevated hydraulic conductivity (e.g., 0.003 m/s [0.01 ft/s]) there is little difference in time to reach maximum production if the hydraulic conductivity is increased by a factor of ten. In summary, if the hydraulic conductivity is sufficiently high, there is an insignificant difference in production rate.



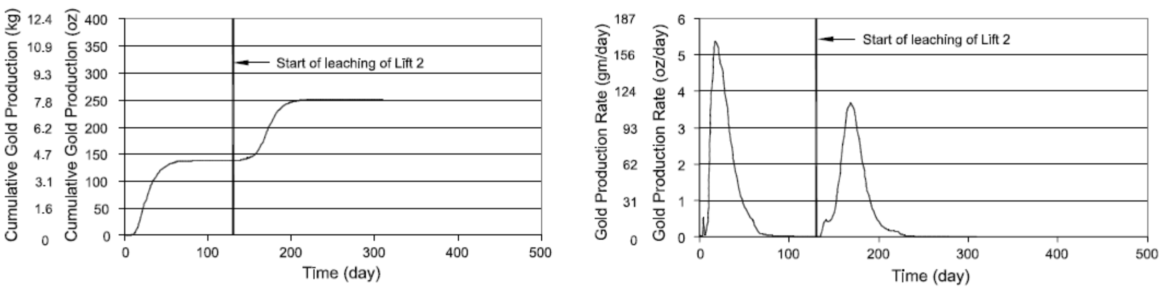
FIGURES 7a and 7b. Scenarios 1 and 2



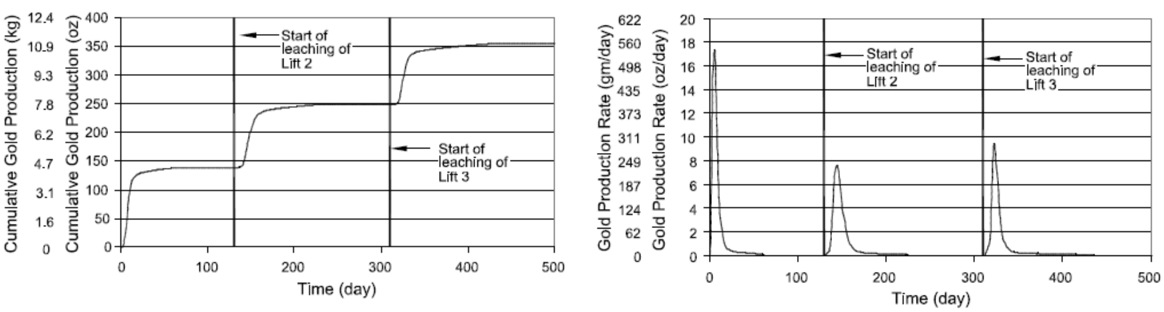
FIGURES 8a and 8b. Scenarios 3, 4, and 5



FIGURES 9a and 9b. Scenarios 6 and 7



FIGURES 10a and 10b. Scenarios 8 and 9



FIGURES 11a and 11b. Scenarios 10, 11, and 12

SUMMARY AND CONCLUSIONS

The initial work on the model incorporated the results of numerous column tests for purposes of calibrating the model to field conditions. The *GHLS* can currently be used to assist in the design and optimization of heap-leach pad design based on hydraulic properties of ore, data on moisture and gold contents, lift height, and lixiviant application rates.

Based upon the simulations conducted for the sensitivity analysis, the following observations and conclusions can be made:

- The more lifts added to a pad results in lower production rates and a longer time for leaching.
- The amount of organic carbon in the ore impacts the gold production rate and the time to leach gold from the lifts. Ores with higher organic carbon contents take

longer times to leach. In order to cut leaching times, the lifts should be lower in height if there is significant organic carbon.

- There is little difference in the time to reach maximum production rates when hydraulic conductivities are elevated. Such a finding suggests that there should be mixing of ores with low hydraulic conductivities with those having high hydraulic conductivities. However, at a certain value of hydraulic conductivity, there is little value in mixing ores with higher hydraulic conductivities.

Lastly, the *GHLS* modeling of the pads demonstrates that it can be used for designing future pads. The optimal heights of pads are influenced by the properties of the materials. For example, for some ores, the maximum pad height for maximum recovery might be in the range of 36 to 45 m (120 to 150 ft) and for others, much less.

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