IMPROVING GOLD RECOVERY WITHIN A CARBON CIRCUIT

*P. Roy [1], A. Berton [1], A. Thivierge[1], M. Troie[2], and A. Morasse[3]

[1]*Soutex,*
357 rue Jackson,
Québec, Canada G1N 4C4 – www.soutex.ca
*(*Corresponding author: proy@soutex.ca)*

[2]*Alamos Gold div. Island Gold,*
Goudreau Road, Dubreuilville, Ontario, P0S 1B0

[3]*Agnico Eagle div. Meliadine Mine,*
Suite 879 - Rainkin Inlet, Nunavut, Canada X0C 0G0

ABSTRACT

Gold has been recovered with activated carbon for many years, a robust process that usually leads to a very high gold recovery mainly controlled by gold adsorption kinetics. It is possible to perform laboratory tests to measure the adsorption kinetics, but the results of this approach are often not representative of the industrial plant scale behavior.

One way to minimize the loss of gold would be to know, once in operation, the real carbon adsorption kinetics, which are influenced by the many operational factors. Indeed, this knowledge would allow the operator to react, diagnose or predict the impact of process changes on performances. By tracking the evolution of gold concentration on carbon and in the solution in each tank, while also reproducing the effect of carbon transfer, or the change in tank order for a carousel type CIP, it becomes possible to estimate the actual kinetic constant of the carbon adsorption in the plant.

This paper presents how a modelling tool, called GLAS (Gold-Silver Leaching and Adsorption Simulator), for CIL and CIP circuits is used to reproduce the behavior of a carbon recovery circuit to analyse the current operation performance and develop alternatives for recovery improvements. The GLAS tool was used in brownfield projects for plant optimisation as well as in greenfield projects for plant design. Examples of the Island Gold and Meliadine projects are presented.

KEYWORDS

CIL/ CIP simulation, carbon adsorption, gold recovery, plant design

INTRODUCTION

Ore mining and milling are energy-intensive activities in an era where humans must rethink their relation to the environment. Once the ore is dug out of the ground and finely milled, achieving the best possible gold recovery is therefore a duty for every mineral processor. Modern analysis tools such as dynamic simulations can be used in order to assist the decision process in finding the best ore processing route.

A dynamic CIL/CIP precious metal simulator was developed and successfully applied in brownfield and greenfield gold mining projects. The first principles behind the simulator are presented as well as the typical programming interface. Then, two (2) successful industrial applications of the simulators are presented. In the case of the brownfield Island Gold expansion, the simulator was used to compare technological solution to a capacity increase while limiting the gold liquid losses. In the case of the greenfield Meliadine construction, impacts on gold recovery of various partial construction schedules were studied. Finally, additional interesting case studies are presented, where the use of the simulator could bring value to the design, diagnostic or daily production of a precious metal concentrator.

MODEL DESCRIPTION

The GLAS (Gold-Silver Leaching and Adsorption Simulator) tool is based on a population balance modeling approach. Three (3) phenomena are considered: leaching, carbon adsorption, and preg-robbing. Mixing and transportation are first explained, and then the reaction models are presented.

Mixing and Transportation

The GLAS tool can be used to model circuits containing leaching, CIP, CIL tanks, and carrousel units. In all cases, tanks are assumed to be perfectly mixed. For leaching, CIP, and CIL tanks, the output flowrate is found assuming constant tank volume. The carbon flowrate is null in normal operation and is a function of pump speed during transfers. As of carrousel units, the flowrates depend on the plant status. The plant status could be either normal operation with all tanks full, or batch operations at the beginning of a carbon transfer or at the end of a carbon transfer.

Reaction Models

Four (4) phase components are tracked in the GLAS: water, solids (excluding graphitic material), graphitic material, and carbon. At each time step, mass balance equations are solved for each tank assuming the following reaction rates:

$$\text{Leaching rate} = M_S\, k_s\, \left(T_S - T_{S,\infty}\right)^{n_l}$$
$$\text{Adsorption rate} = M_C\, k\, (K\, T_L - T_C)$$
$$\text{Preg-robbing rate} = M_{GM}\, k_{preg}\, \left(K_{preg} T_L - T_{GM}^{n_p}\right)$$

where M_S, M_C, and M_{GM} are respectively the mass content of the solids, carbon, and graphitic material (preg-robbing material). T_S, T_L, T_C, and T_{GM} are the concentration of precious metal in the ore, the liquid, the carbon, and the graphite phase respectively. k_s, k, and k_{preg} are the kinetic rate constants for the three (3) reactions. The other variables are empirical parameters. $T_{S,\infty}$ is the theoretical concentration after an infinite leaching time, n_l is the reaction order, K is the equilibrium constant for carbon adsorption, K_{preg} and n_p are the isotherm parameters for the adsorption of the precious metal on the graphitic phase. The leaching, and adsorption model are from Nicol (1984), and the preg-robbing model is from Rees & Van Deventer (2001).

Calibration of Kinetic Constants

To calibrate the GLAS model using plant data, a weighted least-square regression is performed, i.e. kinetic parameters are found by minimizing J using a numerical optimisation algorithm:

$$J = \sum_{i=1}^{N} w_i \left(y_{mes,i} - y_{sim,i}\right)^2$$

where w_i is the calibration weight on measurements $y_{mes,i}$, and $y_{sim,i}$ is the calculated value. The measurements are the liquid, solid, and carbon precious metal grades. The measurements can be dynamic, for example the first tank liquid gold grade could be measured at different time intervals and this information could be used in the calculation of J. The calibration weights are chosen as a function of the quality and accuracy of the measurements. J might have many local minima as the number of calibration parameters is high, thus a typical local solver might be inaccurate. A practical approach to overcome this issue is by subdividing the problem.

First, the circuit is divided into two (2) parts: leaching and adsorption. In the leaching circuit (with only leach tanks, no CIL), the adsorption rate is equal to 0. If there is no preg-robbing material, its rate is also equal to 0. Then k_s, $T_{S,\infty}$, and n_l can be found easily with a local solver. The reaction order is usually 1, 1.5 or 2 and will mostly depend on the mineral (Rees, 2000). The second part of the circuit is the adsorption. In a typical circuit, the reaction is far from the equilibrium (McDougall et al., 1980). Therefore, the adsorption rate becomes:

$$M_C\, k\, (K\, T_L - T_C) = M_C k K T_L - M_C k T_C \approx M_C k K T_L$$

The resulting equation means that the product of kK will dictate adsorption dynamics. A single value of kK will be obtained either for a large K and a small k, or for a small k and a large K. Again, there are many local minima. To overcome this issue, K is fixed at a reasonable value according to literature. Therefore, the kinetic constant k is the only value that is calibrated with the numerical optimiser. Alternatively, the K constant could be determined from a laboratory test.

If preg-robbing material is present, additional laboratory tests are necessary to find the preg-robbing kinetic parameters. The parameters K_{preg} and n_{preg} are found with an isotherm. It is made with multiple tests where the preg-robbing material is put in a batch reactor with a pregnant gold solution in which the liquid and solid grades are measured when the equilibrium is reached. At equilibrium, the preg-robbing rate is 0, thus the following equation can be written:

$$T_{GM} = {K_{preg}}^{1/n_{preg}}\, T_L^{1/n_{preg}}$$

K_{preg}, and n_{preg} are then fitted with the above equation using the equilibrium data obtained during the isotherm. An example is shown in Figure 1.

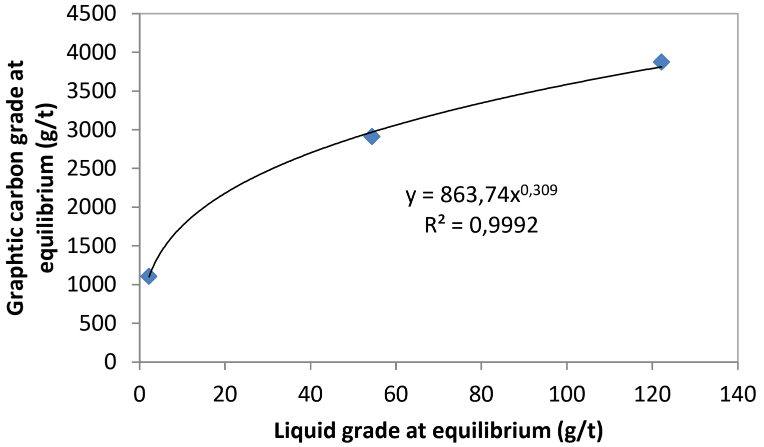


Figure 1 – Example of Adsorption Isotherm with Preg-robbing Material

Then, k_{preg} can be determined by curve fitting the preg-robbing model to the same kind of laboratory tests, but with multiple liquid grade measurements, as shown in Figure 2.

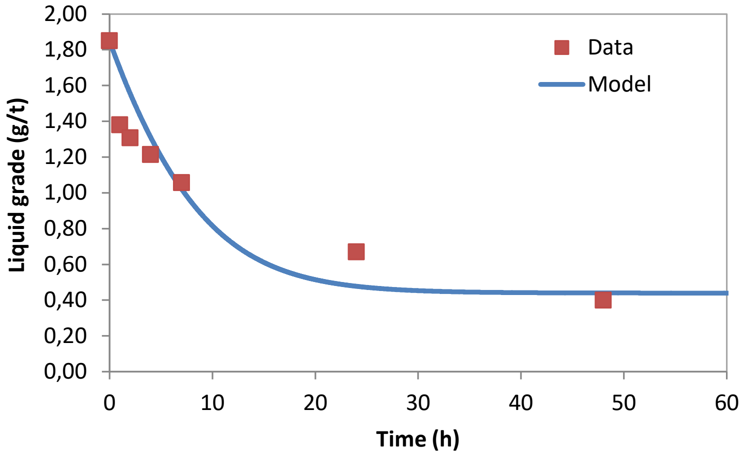
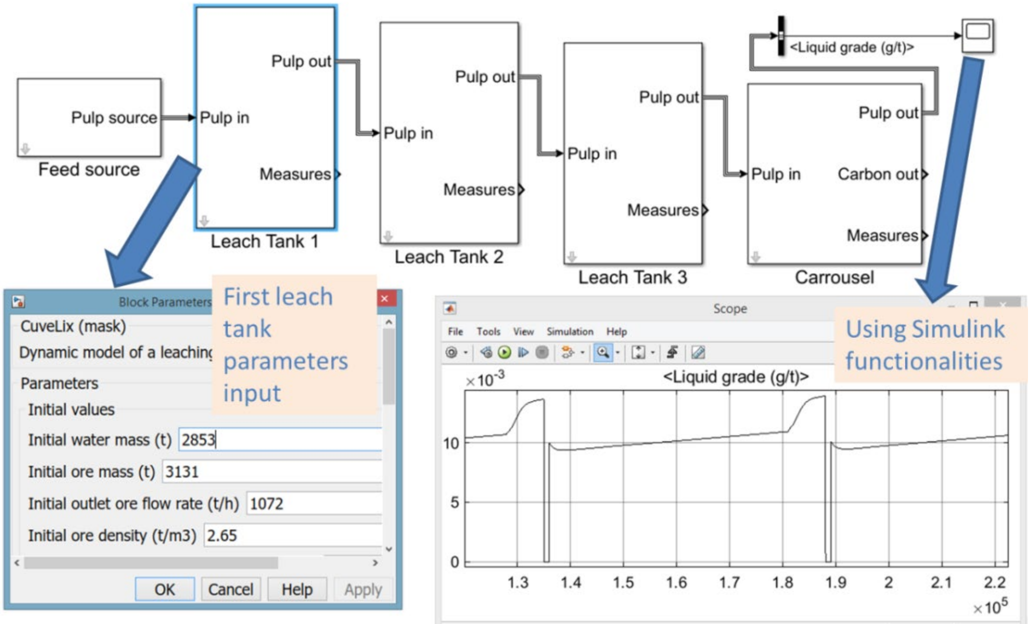


Figure 2 – Preg-robbing Kinetic Test

With the preg-robbing parameters determined, the previous procedure can be followed to find the leaching and adsorption parameters. Regarding the previous calibration procedure, it is assumed that the kinetic constants are the same in all the circuit. If the cyanide or the dissolved oxygen concentrations change significantly, then this assumption will not be true and different parameters should be used within the circuit.

GLAS PROGRAMMING INTERFACE

The GLAS tool is programmed in Matlab/Simulink®. Figure 3 shows an example of the interface where a circuit containing three (3) leach tanks and one (1) carrousel unit (with 7 tanks) is simulated. One advantage of using Simulink is that it gives access to a multitude of tools, from solvers to simple blocks that allow visualisation of the process dynamics such as the “scope” unit shown in Figure 3. The “scope” in this example shows the tailings liquid gold grade as a function of time. The dynamics of the process can be observed: i.e. normal operation where the grade slowly rises because of the carbon loading, a grade spike during transfers when one tank is offline and a small amount of time with a null grade when the circuit has no outflow because the last tank is being filled back up after coming back online. The software also allows the development of a user-friendly parameter interface such as the one shown on the bottom left of Figure 3. Such an interface allows process engineers to use the tool without needing programming knowledge.



First leach tank parameters input

Using Simulink functionalities

CuveLix (mask)

Dynamic model of a leaching

Parameters

Initial values

Initial water mass (t) 2853

Initial ore mass (t) 3131

Initial outlet ore flow rate (t/h) 1072

Initial ore density (t/m3) 2.65

Figure 3 – Example of the GLAS Interface

As mentioned before, the GLAS tool is used to simulate hydrometallurgical processes in a dynamic fashion. The programming environment allows for the flexibility to simulate about any scenario that can be thought of. The tailings liquid grade dynamic response to a step change in the feed ore grade is plotted as an example of such dynamic scenarios in Figure 4. The recovery is also illustrated in green, using 1 on the left axis as 100% recovery.

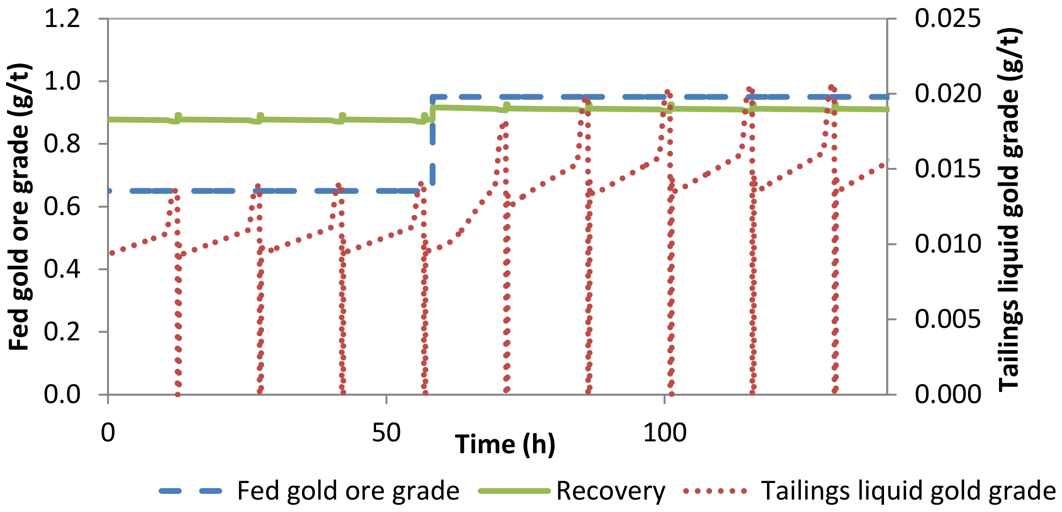


Figure 4 – Example of the Dynamic Effect of the Gold Ore Grade on the Tailings Liquid Grade

BROWNFIELD PLANT UPGRADE APPLICATION

One application of the GLAS tool is presented in a case where the tool was used in order to make a key decision process within the implementation of a plant expansion and for which end results are in the meantime available.

Island Gold Mill Challenge

Back in 2016, Alamos Gold (Richmont Mines at the time) was completing its expansion project of its Island Gold Mine operation from 750 tpd to a nominal 900 tpd. Given the successful results obtained from the expansion, the company wanted to further increase the nominal daily throughput to 1200 tpd. One area that needed to be addressed was the carbon in pulp (CIP) circuit. The gold recovery circuit consisted at the time of five (5) leach tanks, followed by five (5) CIP tanks. The gold was then recovered with a Zadra type elution system. The production increase had to be realized while minimizing Capex and the impact on the overall gold recovery. Without any changes in the circuit, the additional gold input would bring the gold loading in the CIP tanks higher, resulting in increased liquid losses.

Possible Improvement to Improve the Gold Recovery

After a first overview of the possible solutions, three (3) different options were retained for further study. A formal trade-off was realised in order to assess both cost and process performances.

1. The first studied solution was the addition of a gravity recovery circuit at the grinding circuit, which would allow for a portion of the gold to bypass the Leaching/CIP circuit. This solution involves the modification of pumps, cyclones, pumpboxes, piping, and the addition of a screen, a gravity concentrator, pumping devices, a magnetic separator as well as a shaking table. It would also involve one (1) additional operator.
2. The second solution was the addition of adsorption columns at the thickener overflow resulting in a reduction of the amount of dissolved gold reaching the leaching/CIP circuit by recovering around 60% of the gold leached in the grinding circuit. This solution involves the thickener overflow being diverted to a new feed tank, the addition of three (3) adsorption columns, a static screen, and carbon transportation devices. The additional carbon must also be processed in the existing elution circuit.
3. The third option was the conversion of the last leach tank to a CIL which would provide one more stage of gold adsorption on carbon. This solution involves the replacement of the first CIP tank air lift by a carbon pump for the transfer to leach tank #5, the addition of a carbon screen in leach tank #5, and the addition of a carbon transfer pump from leach tank #5 to the loaded carbon screen.

GLAS Calibration and Performance Prediction

The GLAS tool was chosen in order to quantify the benefits of the proposed solutions. Operating data from the concentrator was used to tune the simulator and establish the kinetic constant parameters of the GLAS tool at the nominal throughput (pre-expansion).

Table 1 shows the simulation results when comparing the Au Gold losses for the three (3) options.

Table 1 – Results of Metallurgical Predictions for the Island Gold Au Liquid Tailings

Parameter	Units	Current CIP	Current CIP	Opt. 1: Gravity Circuit	Opt. 2: Adsorption Column	Opt. 3: CIL Conversion
Throughput	%	Nominal	Nom. + 37%	Nom. + 37%	Nom. + 37%	Nom. + 37%
Liquid Au in tails	ppm	0.014	0.035	0.026	0.025	0.017
Au liquid loss	oz/y	130	526	400	377	252
Loss	k$/y	143	579	440	415	278
Gain	k$/y			139	164	301

Economic Analysis of Solution

Following the metallurgical performance assessment, a high level cost assessment of the proposed solutions is presented in Table 2.

Table 2 – Approximate Cost of the Island Gold Studied Options

Scenario	Additional Manpower	CAPEX (k$)	OPEX (k$/y)	Payback Period (y)
No change	0	0	0	0
Opt. 1: Gravity Circuit	2	2 000	300	22
Opt. 2: Adsorption Columns	0	1 000	50	8
Opt. 3: CIL Conversion	0	300	10	1

Since both the metallurgical performances and cost evaluation pointed in the direction of Option 3, the management of Alamos Gold decided to implement the conversion of the fifth leaching tank into a CIL tank.

Metallurgical Performances Obtained

For Option 3, the GLAS predicted Au liquid losses in the range of 0.013 and 0.027 ppm Au (a case at 0.017 ppm is illustrated in Table 1) depending on the feed grade and the various operating conditions. Figure 5 shows the Au liquid profiles along the leaching and CIP circuit for various months before the CIL conversion (full lines) and after the CIL conversion (dashed lines). The first months of operation of the converted CIL tank resulted in higher than expected Au liquid tails. However, after the operating team took full ownership of the new equipment, the Au liquid tails reached pre-expansion levels and even lower.

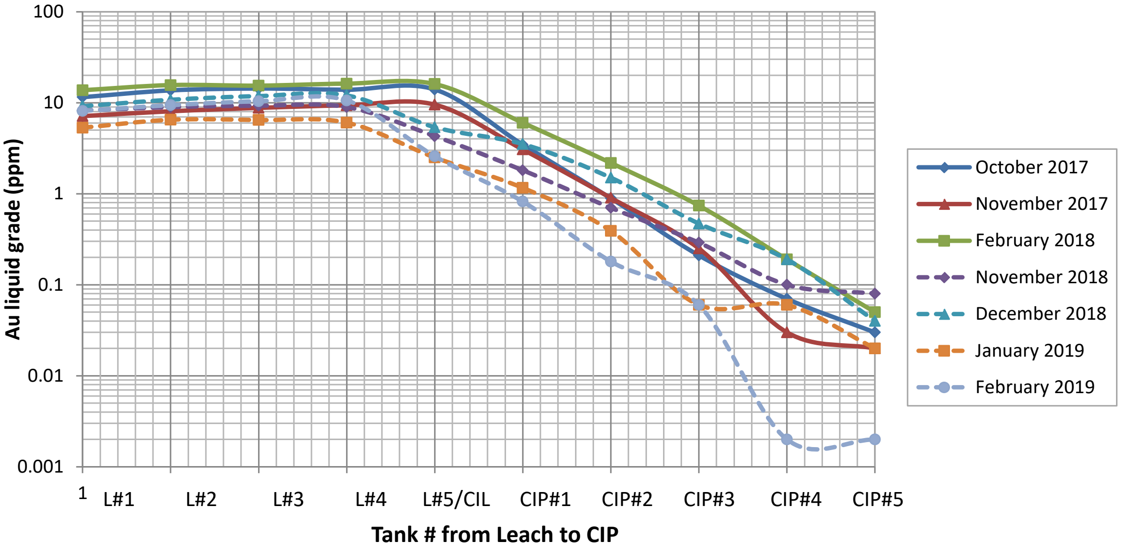


Figure 5 – Au Liquid Grade at Each Tank of the Leaching and CIP Circuit

GREENFIELD PROJECT DESIGN APPLICATION

For the second application of the GLAS tool, a key process decision within the design of a new plant was made with the help of simulation results. End results are, in the meantime, available.

Meliadine Challenge

In 2015, Agnico Eagle, following a review of the basic engineering package, concluded that capital cost (CAPEX) reduction was deemed important to maximize the Meliadine project profitability. The Meliadine gold recovery circuit consisted of a gravity concentration circuit at the grinding stage followed by a CIL circuit made of five (5) CIL tanks. The circuit was designed with the intention of doubling the capacity after 4 years of operation by adding more CIL tanks and the elution circuit was already built to its final capacity. Among the options that were part of the cost reduction initiative, was the use of one (1) CIL tank as a clarifier surge tank during the first four (4) years, which would help postpone the construction of the envisioned tank hence reducing the initial CAPEX. It was, however feared that such a change could impact the global recovery performance of the plant. Only the liquid gold losses were considered in this study as the leaching residence time did not appear problematic.

Possible Process Layout to Optimize the CAPEX Figures

To predict the impact on liquid gold recovery, the GLAS tool was chosen to assess the liquid gold losses for various scenarios of cost reduction:

1. Removing 1 of the 5 CIL tanks (4 CIL);
2. Scenario 1 and removing the batch gravity circuit (4CIL+No Gravity);
3. Mitigation options (with 4 CIL tanks and no gravity circuit) like increasing carbon inventory (×2) and stripping capacity. (Optimized Carbon + Stripping);
4. Evaluation of the operation at a 25% tonnage increase to validate design flexibility (High Tons + 4 CIL + No Gravity).

In addition, evaluation of the impact of having one (1) CIL tank off line on maintenance thus operating temporarily with only three (3) tanks was performed (not in Table 3).

GLAS Calibration and Performance Prediction

The GLAS tool was chosen in order to quantify the benefits of the proposed solutions. For this application, the dynamic simulation model was calibrated on leaching and carbon adsorption kinetic constants obtained from testwork. Table 3 presents the simulated performances for Au liquid losses for the various options.

Table 3 – Metallurgical Predictions for the Meliadine Au Liquid Tailings

Parameter	Units	Base Case	4 CIL	4 CIL+ No Gravity	Optimized Carbon + Stripping	High Tons + 4 CIL	High Tons + 4 CIL+ No Gravity
Throughput		Nominal	Nominal	Nominal	Nominal	Nom.+25%	Nom.+25%
Liquid Au in tails	ppm	0.012	0.019	0.027	0.023	0.028	0.043
Au liquid loss	oz/y	77	128	183	153	234	358
$ liquid loss	k$/y	96	160	228	192	292	447
Loss vs. base case	k$/y		(64)	(132)	(96)	(127)	(283)

In addition to figures provided in Table 3, the evaluation of maintenance on one of the CIL tanks, resulting in having only 3 tanks in operation, predicted a liquid loss of 1.25 oz/day.

Plant Implementation and Performances Obtained

Combining the results presented in Table 3 with the foreseeable additional loss in solid tailings, the Meliadine team decided for the first years of operation to implement four (4) CIL tanks along with the gravity circuit consisting of two (2) batch concentrators and a continuous gravity concentrator aiming at regrinding the dense fraction prior to CIL. Recent results from the Meliadine plant with four (4) CIL tanks and no gravity circuit yet showed gold liquid losses of 0.02 ppm. This result is in the same range as the prediction provided in Table 3 (4 CIL + No Gravity: 0.027 ppm).

FORSEEABLE VALUABLE ADDITIONAL APPLICATIONS

This section gives a few examples of how the GLAS can be used to answer typical gold processing optimisation questions. Three (3) case studies are presented: preg-robbing mitigation, the effect of ore feed grade homogeneousness and the calculation of gold losses during tank bypass for maintenance.

Preg-Robbing Mitigation

To deal with a preg-robbing ore, typical solutions include adding reactants or even changing the process to maximise active carbon contact with the pulp, such as converting leach tanks to CIL. The presented theoretical example consists of one (1) leach tank, nine (9) CIL tanks, has preg-robbing issues from about 0.2% of graphitic carbon present in the feed ore, and the residence time is about 29 h. Two (2) solutions are proposed: bypassing the leach tank, or converting the leach tank to CIL. The results are presented in Table 4.

Table 4 – Results of a Theoretical Case Study

Scenario	Tailings Solid Grade (g/t)	Tailings Water Grade (g/t)	Total Gold Mass Flow in Tailings (g/h)	Variation of Total Gold in Tailings (%)
Base case	0.2176	0.004243	237.63	0,00%
Leach tank by-pass	0.2156	0.005348	236.56	-0.45%
Leach tank conversion to CIL	0.2087	0.003544	227.40	-4.31%

Bypassing the leach tank will mostly simply reduce the residence time of all three (3) reactions. This results in a lower ore grade and a higher liquid grade. The lower ore grade is caused by the reduction in the preg-robbing reaction, i.e. there is less gold in the graphitic phase of the ore. The higher liquid grade is caused by the reduced completion of the adsorption and preg-robbing reactions. Overall, the net effect is a reduction in mass flow of gold in the tailings, albeit by a very hard to measure margin.

On the other hand, the conversion to CIL reduces both tailings water and solid grades. The lower tailings ore grade is explained by the extra carbon adsorption stage in the circuit. In addition, there is no leaching tank where the graphitic carbon is not in competition with activated carbon. The effect of these two phenomena results in an increased recovery of the gold by the activated carbon, which results in less gold being preg-robbed. The graphitic material being poorer then translates to a lower tailings grade. Similarly, this increased recovery from the activated carbon is also responsible for the diminution of the liquid grade. In summary, the conversion to CIL is efficient to reduce the amount of gold in the tailings, although extra capital costs are expected.

Effect of Feed Grade Spikes

It makes sense to assume that a more homogenous grade will lead to greater economic performances, i.e. that a grade spike in the fresh ore should be avoided when possible by implementing a proper material handling plan. This is a common practice for base metals, for instance, when flotation is used. This case study presented in Figure 6 attempts to verify this belief in the case of gold.

For the same theoretical plant, consisting of one (1) leach tank and nine (9) CIL tanks, three (3) illustration cases are simulated. The first case illustrates a strong gold spike of an extra 1 g/t/h of gold for 29 h which is approximately the residence time (τ) of the circuit. The second and third cases illustrate the effect of attenuating the gold spikes on 290 h (10 τ) and 1450 h (50 τ), which could be realised by blending the material. The plain lines represent the plant feed grade and the dashed lines represent the cumulative gold loss.

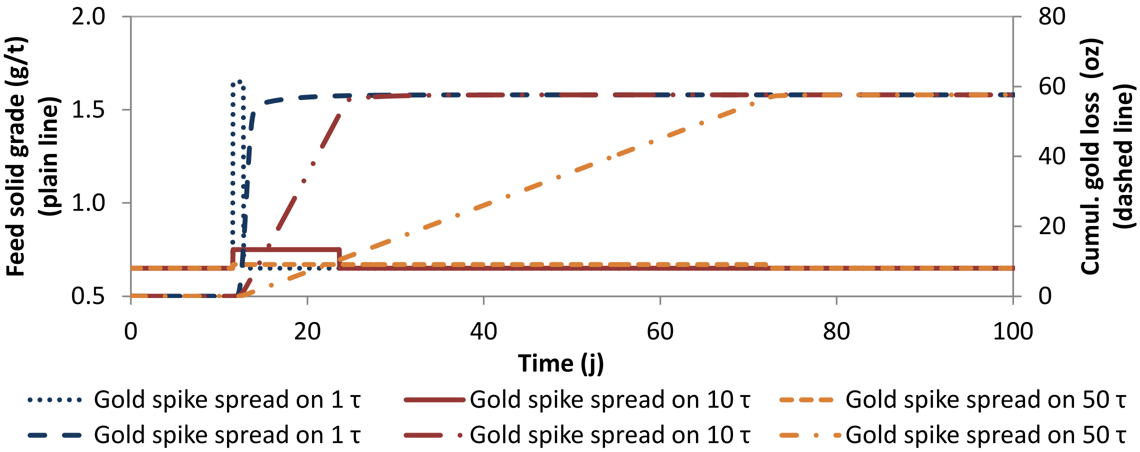


Figure 6 – Effect of a Grade Spike on Gold Losses of a CIL Circuit

Figure 6 shows that about the same additional gold losses will occur for a grade spike whether it is managed by blending or not. These results are obtained because the reaction kinetics depend on the solid and liquid grades. A higher solid grade increases leaching speed, and a higher liquid grade proportionally increases adsorption speed, therefore the typical circuit will not benefit much from mixing material, especially if re-handling and storage costs are factored into the analysis.

However, if carbon loading increases above a certain threshold, its adsorption capacity becomes limited. As a result, the activity will decrease (i.e., K will decrease), and the adsorption reaction will slow down. In such cases, it is possible that mixing material becomes beneficial. Using operation data, the GLAS tool could be calibrated with K fitted as a function of carbon loading to study those unusual scenarios.

Different factors influencing the threshold are discussed in Fleming (1984). They include pH, solution ionic strength, temperature, and competition from copper cyanide.

Gold Losses during Tank Shutdown

The GLAS tool can be used in order to determine an optimal maintenance schedule, making a trade-off between gold losses resulting from a tank shutdown and gold losses from equipment having lower performances when not maintained as often. To find this optimal sequence, the losses occurred during a shutdown must be quantified, which can be done using the GLAS tool. The simulated example circuit contains three (3) leach tanks and a carrousel unit of seven (7) cells (adsorption residence time of 25 mins). Figure 7 shows the simulated effect of bypassing a tank for shutdown between two (2) transfers (for 14.75 h during day 1).

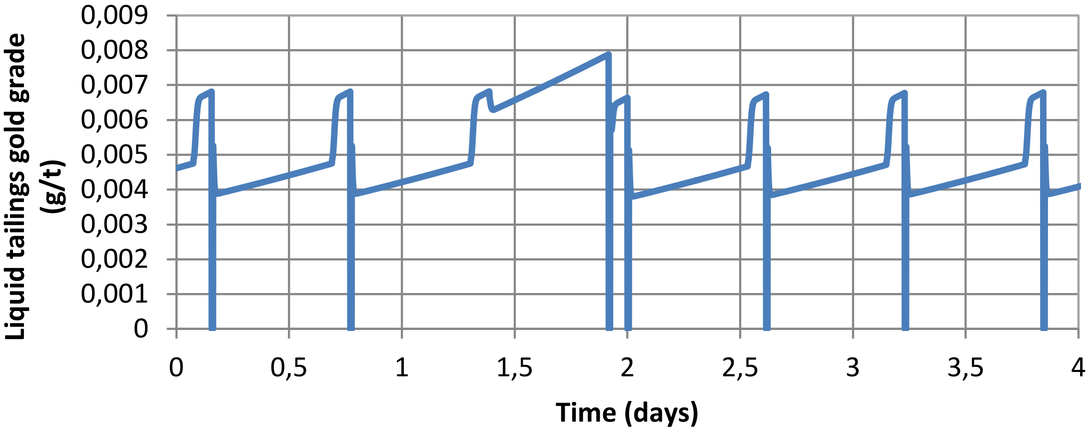


Figure 7 – Effect of a Tank Shutdown between Two Transfers on Liquid Tailings Grade

Figure 7 shows that the liquid tailings grade increases significantly during the shutdown. Following the shutdown, the liquid tailings are slightly lower for about two (2) cycles. The higher grade during the shutdown is expected, as one (1) adsorption stage out of seven (7) is not available. The slightly lower grade afterward is caused by the higher proportion of fresh carbon in the circuit, since the last two (2) tanks are filled up with fresh carbon at the end of the shutdown. Overall, net losses from this shutdown represent about 1.1 gold ounces, which is approximately 33% of normal day liquid gold losses (the gold in the ore tailings is largely unaffected as the leaching reaction is assumed completed in the carrousel unit).

CONCLUSION

A dynamic CIL/CIP simulation tool for precious metal recovery prediction was developed and successfully applied to two (2) different industrial cases, the brownfield Island Gold case and the greenfield Meliadine case. In addition to the presented industrial applications, three (3) other potential applications were described, showing the GLAS tool ability to handle preg-robbing issues and practical operation challenges.

The applicability of the GLAS tool is however not limited to the presented cases it has already been applied to:

- Detection of a seasonal effect on the adsorption kinetics, leading to two (2) different kinetic constants for summer and winter at a Canadian carrousel type CIP circuit;
- Carbon management optimisation for a West African CIL plant (simulation of various carbon concentrations);
- Simulation of increased throughput through the CIL circuit for a West African gold plant.

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