CHAPTER 10.11

Carbon Adsorption

Matthew Jeffrey

In extractive metallurgy, the dominant use of activated carbon is in the adsorption of the gold cyanide complex from aqueous solution following the cyanide leaching of gold ores. The historical development of activated carbon adsorption in gold metallurgy has been well described by Marsden and House (2006), who highlight the very rapid take-up of the carbon-in-pulp (CIP) technology from the 1970s throughout the United States (with the Homestake mine in South Dakota being regarded as the birth of modern CIP), South Africa and Australia. By the 1990s, most new gold processing plants constructed used some form of the carbon adsorption technology, either as CIP, carbon-in-leach (CIL), or carbon-in-column (CIC). CIP and CIL both make use of carbon directly in a leach slurry, whereas CIC circuits are used to recover gold from pregnant solutions (usually from heap leach operations). Figure 1 shows a block flow diagram of an oxide gold mill with a CIL circuit, where carbon is added to each leach tank to adsorb the gold cyanide complex. The carbon is recovered from pulp by screening and then acid washed to remove inorganic contaminants (e.g., carbonates) prior to recovery of gold from the carbon by elution and electrowinning.

Although this chapter exclusively deals with the application of activated carbon for gold adsorption, readers are reminded that activated carbon is also a very powerful adsorbent for off-gas treatment applications, for example, the removal of volatile organic compounds (Shepherd 2001). In addition, several modern mineral processing plants employ sulfur-impregnated activated carbon (SIAC) for the capture of mercury in off-gas treatment systems, especially those servicing gold rooms and carbon regeneration furnaces. In Newmont-affiliated facilities, SIAC systems can be found at operations with mercury present in the ore, for example, Twin Creeks and Carlin in Nevada, United States. For further information on SIAC systems, the reader is referred to Krumins et al. (2014).

The intent of this chapter is to provide a short summary of background theory and then focus on the metallurgical testing and principles used in modern gold processing plant design. Finally, some key examples of operating plants are presented that deal with a range of different and complex ore feeds. The detailed design of the complete carbon adsorption, desorption, and gold recovery circuits used in modern plants is covered in Chapter 10.12, “Carbon-in-Leach and Carbon-in-Pulp Circuit Design.”

BACKGROUND THEORY

Activated carbon is produced through the high-temperature activation of a carbonaceous source, producing an extremely high surface area, porous product. The most common activated carbon used in gold processing applications is derived from coconut shell typically having a BET surface area (internal and external surface area measured by gas adsorption according to the method of Brunauer, Emmett, and Teller) of 900–1,000 m^2/g (Marsden and House 2006). Several good publications outline the theory of carbon adsorption of gold cyanide; examples recommended for further reading include Marsden and House (2006), Staunton (2005), and Fleming (2002). Hence, only a summary is presented here.

Adsorption and Desorption of Gold

Although there has been debate in the literature, it is now widely accepted that gold cyanide adsorption onto activated carbon occurs via an ion-pair mechanism, which explains the increased affinity for gold in the presence of cations commonly present in cyanide leach solutions such as Ca^{2+} (McDougall et al. 1980). The adsorption reaction is also reversible and exothermic, with the loading capacity decreasing with increasing temperature and free cyanide concentration as well as with decreasing ionic strength. These factors are key in the design of elution circuits, whereby high temperatures and either high-cyanide or low-ionic-strength solutions are adopted to strip or desorb the gold from carbon.

Kinetic and Equilibrium Considerations

The loading of gold onto carbon, a heterogeneous reaction, occurs by several key reactions steps:

1. Mass transport of the gold cyanide complex (or ion pair) from the bulk solution to the outside carbon. This reaction is first order and dependent on the mass transfer coefficient, which is primarily governed by agitation.

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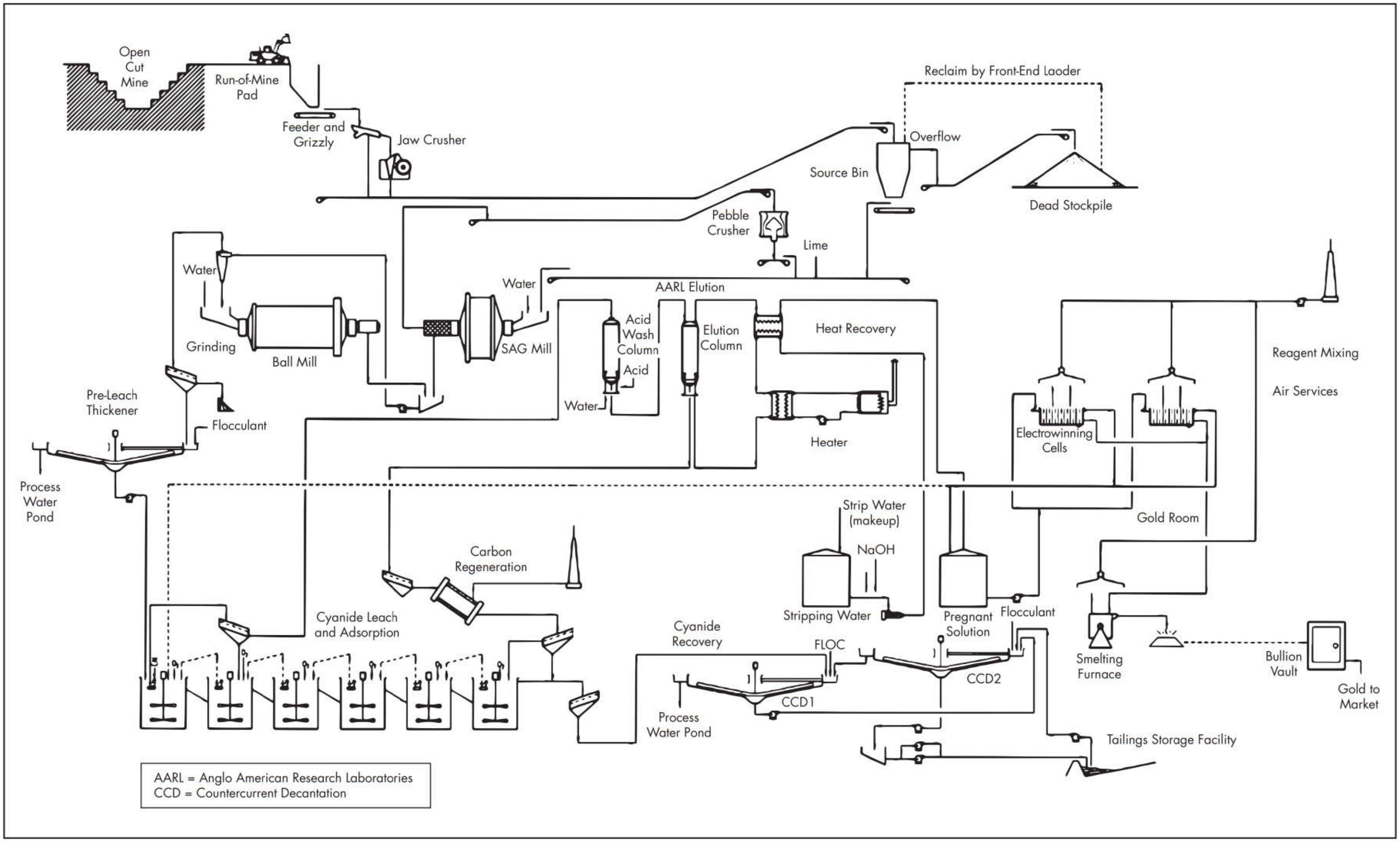

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Figure 1 Block flow diagram of a typical gold processing circuit using carbon adsorption

2. Adsorption of the gold complex onto the carbon surface, which is a chemical reaction for which the reaction rate is also first order with respect to gold concentration.

These two steps account for the loading of gold around the perimeter of the carbon particle. However, after the outside surface sites of the carbon are occupied, internal surface sites must be used for further adsorption, either by the solution or surface diffusion of gold down into the small-diameter pores. This step is slow in comparison to the first two steps, which account for loading of gold on the outside of the carbon. X-ray tomography images have shown that at 2,500 g/t gold loading, the adsorption is primarily isolated to the outside surface of the carbon to a depth of nominally 200 µm (Pleysier et al. 2008). Vegter and Sandenbergh (1996) have argued that the internal structure of the carbon becomes loaded via the surface diffusion mechanism, which was based on a comparison of mass transfer rates for surface diffusion versus solution diffusion down very narrow pores. X-ray tomography at high loadings (25,000/t) is consistent with this theory, as the internal structure was very evenly loaded and independent of the differences in carbon pore sizes.

The adsorption of gold on carbon ultimately reaches an equilibrium loading, for which the gold loaded on carbon ($[\mathrm{Au}]_C$) is a function of the concentration of gold remaining in solution ($[\mathrm{Au}]_{\mathrm{aq}}$), and the empirical Freundlich isotherm shown in Equation 1 has been demonstrated to represent the equilibrium very well:

$$[\mathrm{Au}]_C = K[\mathrm{Au}]_{\mathrm{aq}}^{\,n} \qquad \textbf{(EQ 1)}$$

where K and n are the Freundlich isotherm parameters. At 1 mg/L gold in solution, the gold on carbon is K g/t.

Modeling of Carbon Adsorption

The well-known Nicol–Fleming model (Nicol et al. 1984) has been used for modeling gold adsorption for several years. The model is based on the adsorption rate being a steady-state first-order reaction that approaches an equilibrium constraint as described by a Freundlich isotherm, as shown in the following equation:

$$d[\mathrm{Au}]_{\mathrm{aq}}/dt = k[\mathrm{C}]([\mathrm{Au}]_{\mathrm{aq}} - [\mathrm{Au}]_E) \qquad \textbf{(EQ 2)}$$

where

k = rate constant (mass transfer coefficient) for adsorption
$[\mathrm{C}]$ = concentration of carbon, g/L
$[\mathrm{Au}]_E$ = equilibrium solution gold concentration at the equilibrium gold loading on carbon

Substituting for the isotherm and applying to a well-mixed continuous stirred tank reactor (CSTR), the following equation is obtained:

$$[\mathrm{Au}]_0 - [\mathrm{Au}]_{\mathrm{aq}} = k\tau\,[\mathrm{C}]([\mathrm{Au}]_{\mathrm{aq}} - K[\mathrm{Au}]_{\mathrm{aq}}^{\,n}) \qquad \textbf{(EQ 3)}$$

where

$[\mathrm{Au}]_0$ = gold in solution concentration available for adsorption, which includes the gold leached in the contactor
τ = retention time of the contactor

This is combined with the mass balance for gold, resulting in two equations with two unknowns ($[\mathrm{Au}]_{\mathrm{aq}}$ and $[\mathrm{Au}]_C$). The model is simple to implement and has been shown to represent CIL/CIP plants very well, particularly at the lower gold loadings obtained in most processing operations. The model is also the basis of the SIMCIL model discussed by Staunton (2005) and used in the AMIRA P420 project (a collaborative industry project coordinated by AMIRA International, which commenced in 1990 and was still running at the time of publication). The SIMCIL model is a steady-state mass balance that incorporates the CSTR adsorption model into a web-based platform. To improve the model, Dai et al. (2010a) have published corrections to the equilibrium isotherms based on the impact of ionic strength of the solutions and the competitive adsorption of copper, which can have a significant impact on the gold loading. More sophisticated dynamic and population balance models have been developed that account for the periodic nature of carbon transfer in processing plants (Stange et al. 1990), but these have not found widespread use by operators.

Co-Adsorption and Fouling

Carbon adsorption operations become more complex when the feed

- Contains high silver that needs to be recovered,
- Contains high levels of cyanide-soluble copper,
- Is a flotation concentrate or tails that contain flotation reagents (organics), or
- Contains other carbonaceous matter that contributes to the phenomenon known as preg-robbing.

The operation of such facilities is described later in this chapter, and the background theory for these more complex feeds includes the following:

- The adsorption of the silver cyanide complex formed when leaching silver from the ore is significantly weaker than observed for the gold cyanide complex. This is one reason the Merrill–Crowe process is still used for many high-silver applications. If carbon adsorption is to be used, higher rates of carbon transfer are required for effective operation, resulting is larger elution circuits. This is a second reason for considering Merrill–Crowe over carbon alternatives. Modeling of gold–silver circuits has met with mixed success because of the dependence of silver loading on gold loading, as gold can displace silver on carbon at higher loadings.
- The different complexes of copper (the di-, tri-, and tetra-cyanocopper species) have an affinity for carbon that decreases as the coordination number increases. For this reason, carbon may be used to adsorb the $\mathrm{Cu(CN)_2^-}$ complex if desired, but in gold operations the cyanide strength is usually maintained such that the $\mathrm{Cu(CN)_3^{2-}}$ and $\mathrm{Cu(CN)_4^{3-}}$ complexes are dominant to minimize the adsorption of copper. Modeling of these circuits is even more complex than gold–silver circuits, as demonstrated by Dai et al. (2010b) in the development of a mechanistic copper cyanide loading model.
- Organics, such as flotation frothers and collectors, readily adsorb onto activated carbon, which results in "fouling" of the carbon (La Brooy et al. 1984). Therefore, higher rates of carbon transfer are usually targeted when feeding a CIP or CIL circuit with flotation concentrates or tails, resulting in lower gold loadings. Under such exposure to organics, maintaining the correct carbon reactivation conditions becomes paramount to ensure organic degradation.

- Preg-robbing ores are very common and the key consideration when processing is to ensure that the gold is adsorbed onto carbon as quickly as possible after leaching by maintaining a high carbon concentration in the tanks and typically using low carbon loadings. Dunne et al. (2013) have presented a detailed summary of a range of operations treating preg-robbing ores.

METALLURGICAL TESTING AND MODELING

The following sections deal with the key metallurgical working, including laboratory testing and modeling, which are recommended for the design of new carbon adsorption circuits or for characterization/optimization of existing circuits.

Laboratory Testing for New Circuits

In designing a carbon circuit, three key parameters need to be determined:

1. The gold on loaded carbon, which sets the carbon transfer rate and size of the elution circuit.
2. The gold in barren solution, which is termed "solution loss" and contributes to the economics of the project.
3. The carbon concentration in the tanks, which determines the gold hold-up on carbon in circuit and the required carbon inventory.

Unfortunately, it is very difficult to determine all of the preceding design criteria from laboratory testing alone, for the following reasons:

- The carbon and slurry (or solution) in a plant move countercurrently, with the retention time of carbon usually 10–15 times that of the slurry.
- The mass transfer coefficient for adsorption is important in determining the kinetics of gold adsorption on carbon, and at bench scale it is usually significantly higher than that observed in a full-scale plant.
- Standard CIL/CIP bottle roll tests conducted with typical 10-g/L carbon produce loadings that are only a fraction of that observed in a plant. For example, a 1-g/t gold ore with 90% of the gold being cyanide extractable will produce loaded carbon of around 48 g/t at 40% solids. This is closer to the conditions normally seen in the back end of a CIL/CIP plant.
- Virgin carbon, which is almost always more active than plant carbon, is usually used in laboratory tests.

To address some of these issues, tests will often be conducted with various carbon concentrations, which will produce different points on an isotherm of gold on carbon versus gold in solution. This method is often used to identify whether fouling of the carbon is an issue, as evidenced by a poor isotherm plot. The downside to this method is that if any preg-robbing material is present in the ore, the data will be unduly impacted, because the tests are carried out at low carbon concentrations. If this is the case, the staged contact approach is often adopted, whereby several batches of slurry are leached consecutively with the same batch of carbon to slowly load the carbon at the expected or design carbon concentration (as occurs from the back to the front of a full-scale carbon circuit). Obviously, this approach entails a significant quantity of work and a higher demand of sample for each sample tested, and it is usually used only if the simpler testing shows issues with loading.

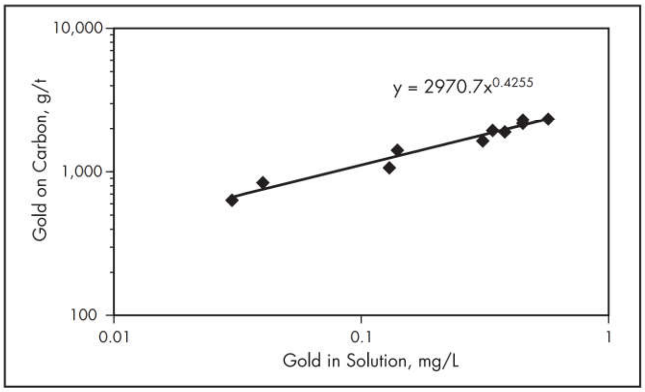

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Figure 2 Laboratory-determined gold loading isotherm for a greenfield project

One word of caution: Although all the testing methods give good information on adsorption isotherms, they do not represent the carbon adsorption kinetics well because of mass transfer differences between laboratory equipment and a full-scale plant. Thus, modeling and relevant benchmarking are highly recommended for supplementing the design of a carbon circuit, with information on isotherms obtained from testing providing an input to the model. In addition, the determination of laboratory isotherms using solutions alone should only be used in CIC applications; that is, testing for CIL/CIP must use slurry, as this does impact the adsorption isotherm. In addition, because carbon adsorption is dependent on the solution constituents and ionic strength, testing solutions should represent as much as possible the likely process solution.

An example where carbon adsorption testing was conducted on a greenfield project is shown in the data in Figure 2, the adsorption isotherm for two of the key ore types overlaid. In this case, the isotherm is much flatter than usually observed, possibly because of the saprolite ore containing fine clays. Even without detailed modeling, this data can be used to determine a starting point for the loaded gold on carbon. At the design percentage solids and retention time, the pregnant solution feeding the first carbon contactor contains 0.6 mg/L gold. A good rule of thumb is that the first contactor should load 30%–40% of the gold. For this example, if we want to load 40% of the gold in the first CIL tank, the gold solution grade in the first contactor would be 0.36 mg/L, with an equilibrium gold on carbon from Figure 2 of 1,923 g/t. The actual gold on carbon would be less than this, as equilibrium is not reached within the contactor because of the short retention time of 2–3 hours (in CIL), as compared to the 72-hour retention time used to obtain the equilibrium isotherm. Based on the rate equation for adsorption in a well-mixed CSTR, the loaded gold on carbon can be estimated, as shown in Equation 3.

For a simple CIL circuit with good carbon activity, a mass transfer coefficient $k = 0.1$ L/g/h has been found to model the adsorption kinetics well from an extensive database of plant surveys from CIL circuits. At a 2-hour retention time per contactor, and 10 g/L carbon, the value of $kt[C] = 2$, that is, $[Au]_C = 1{,}728$ g/t. However, in this example the gold isotherm indicates poorer adsorption performance, and the actual laboratory kinetic testing gave $k = 0.1$ L/g/h, indicating that the plant k will be lower, because in a full-scale CIL plant the mass transfer coefficient is always less than that obtained in a very well-agitated laboratory reactor. Therefore, in this example, choosing $k = 0.05$ L/g/h, the gold on loaded carbon is calculated to be 1,200 g/t from Equation 3, which is a good starting point for the design of the circuit. For this project, after extensive modeling and optimization, a loaded carbon grade of 1,150 g/t was planned. An estimate of gold on loaded carbon enables the preliminary sizing of the carbon transfer and hence elution/regeneration circuit.

Laboratory Testing for Plant Performance

Testing of plant carbon properties is important to understand the performance of the plant carbon circuit. It is important to consider the impact that an operating environment has on these same properties when using test data for plant design and optimization. The types of tests adopted are well covered by Staunton (2005) and involve measuring the rate of adsorption (k) of gold from a solution using a reproducible laboratory experimental setup. Similar to the earlier discussions in this chapter concerning the mass transfer coefficient, the rate constant obtained is somewhat meaningless, which is why the percentage carbon activity is reported as the rate constant for the carbon being tested divided by the rate constant for fresh carbon tested under exactly the same experimental conditions. Staunton (2005) also outlines other carbon characterization tests that have been used in the past, such as abrasion resistance and iodine number. These, however, are not routinely used in industry but are more important to carbon suppliers.

Carbon Adsorption Circuits

The conventions used in distinguishing CIP from CIL in this chapter are as follows:

- **CIP:** A circuit for which leaching is essentially complete prior to contact with carbon. Usually, the retention time of solids in each carbon contactor is low, resulting in smaller tanks than used for leaching. For example, the Kemix pump cell contactors may have as low as 15 minutes per stage retention time (Dippenaar and Proudfoot 2005). To compensate for short retention time of solids, a higher carbon concentration in each contactor is used (typically >20 g/L, and up to 50–60 g/L). The product of retention time and carbon concentration ($C\tau$) is typically as low as 15–20 hours g/L.
- **CIL:** A circuit for which leaching is occurring during contact with carbon. Usually, the retention time of solids in each contactor is high to allow complete leaching, resulting in large carbon contactors (often the same size as leach tanks). Typically, lower carbon concentrations in each contactor are used (<20 g/L). A very common CIL configuration is two leach-only tanks and six CIL tanks. The mass transfer coefficient in CIL is usually lower than CIP, with $C\tau$ needing to be higher (e.g., 30–40 hours g/L) to compensate.

During early-stage studies for gold plants, often the starting point for scoping the carbon adsorption circuit is estimating the rate at which carbon is taken out of the circuit, stripped, reactivated, and placed back into the circuit, which is determined from the gold on loaded carbon. It is common to use a benchmarked "upgrade ratio" in choosing a suitable gold on loaded carbon, where the upgrade ratio is concentration of gold on carbon divided by the gold in solution feeding the first carbon contactor. This method is only recommended as a starting point, with detailed modeling required to support the detailed design (discussed in Chapter 10.12, "Carbon-in-Leach and Carbon-in-Pulp Circuit Design"). For CIL applications, the upgrade ratio should also consider the gold that leaches in that stage. It is also common to report upgrade ratios as gold on carbon divided by gold in the feed ore, but this approach depends on the percentage of solids in the contactors and the gold extraction from ore to solution. Hence in benchmarking, it is better to convert to an equivalent pregnant solution grade to calculate the upgrade ratio. A typical CIL plant is usually designed with an upgrade ratio around 1,500–3,000. In the greenfield site discussed earlier, the upgrade ratio was 1,920. Obviously, if the modeling produced an upgrade ratio outside of the range of most commercial plants, more work would be warranted.

Mass transfer is a very important aspect of the design of a commercial plant, and in practice, the power input into agitation to maintain solids in suspension (given the slurry density and viscosity) effectively fixes the mass transfer coefficient, unless a more vigorous agitation system is used, such as the Kemix pump cells often used in CIP plants (see, e.g., Rogans and McArthur [2002]). Thus, the key driver for increasing the adsorption rate if the number of stages is fixed is to increase the carbon concentration in the contactor, as shown in Equation 3. When designing a plant, the objective is to optimize the carbon concentration so that the adsorption kinetics are fast enough to produce a low gold in barren solution. This is often a trade-off between the number of contact stages (capital cost) and the carbon concentration, with lower carbon (and hence gold) inventory achieved with more stages.

The physical aspects of CIL/CIP design, such as tank agitation, interstage carbon transfer, and interstage screening, are described by Altman et al. (2002) and Altman and McTavish (2002) and discussed in Chapter 10.12, "Carbon-in-Leach and Carbon-in-Pulp Circuit Design."

CIC Circuits

Kappes (2002) reported that in a survey of 28 CIC operations, the average pregnant leach solution (PLS) grades were 0.7 mg/L gold, and average loaded gold on carbon was 3,900 g/t. This corresponds to an upgrade ratio on average of 5,570, which is significantly higher than that obtained for CIL applications. Ultimately, the upgrade ratio used will depend on the desired barren solution grade that is recycled back to the leach pad, the number of CIC contactors in series, and the activity of the carbon (i.e., fouling and regeneration frequency). Similar to CIL and CIP, detailed modeling will be used for the design. Most commonly, four to six contactors are used. For example, at the Newmont Carlin operations, six CIC contactors are used in series, with two to three parallel trains, depending on the PLS solution flow.

Modern CIC plants are usually composed of standard off-the-shelf columns to accommodate the correct solution flow rate. This is an important factor, as a well-chosen column will produce some fluidization and bed expansion of carbon in the column. Bed expansion/fluidization should not too be so vigorous as to cause issues with plugging of overflow screens if present, or carryover of carbon if not. A typical maximum value of 30% bed expansion can be used to provide conditions with good mass transfer, with Ritson (2013) showing correlations for bed expansion with upward flow velocity as a function of carbon particle size, and Kappes (2002) showing the bed expansion as a function of temperature. The packed bed density is typically around 0.5 t carbon/m^3, which can be used to determine the carbon inventory in each contactor based on the column height and allowing for bed expansion. This information will usually be provided by the CIC manufacturer or engineering company and enables the carbon retention time per contactor to be determined, with two to three days per contactor often being regarded as a reasonable maximum to maintain carbon activity and very high upgrade ratios. For example, at one of the historical Newmont operations, an upgrade ratio of around 11,000 was obtained from a feed of nominally 0.6 mg/L gold, with six columns containing 1.8 t carbon each. Carbon was transferred at 1 t/d, giving around 1.8 days per contactor carbon retention time.

CIL/CIP Circuits

Details of designing CIL/CIP circuits are provided in Chapter 10.12, "Carbon-in-Leach and Carbon-in-Pulp Circuit Design"; however, an example of the importance of modeling and carbon adsorption parameters for predicting performance and optimizing CIL/CIP circuits should not be overlooked. To demonstrate the power of modeling, the following example has been developed.

A simple oxide mill/leach/CIL circuit with 50,000 t/d and 1 g/t gold has been designed. The feed to the circuit is 50% solids, and no preg-robbing was observed during the testing campaign, so a simple circuit with three leach tanks and seven adsorption tanks has been selected. A 20-t elution column has been selected, giving a loaded carbon grade of approximately 2,000 g/t. The barren carbon is expected to contain 40 g/t gold, which is typical for a well-operated elution circuit. All the tanks are 5,000 m^3 each to provide the required retention time required to leach all the cyanide-extractable gold. In this example, standard adsorption parameters (for the isotherm and adsorption rate based on the database available of operating simple oxide circuits) have been used for demonstration purposes, and the calculated barren solution grade is 0.012 mg/L at a carbon concentration of 13.7 g/L for each tank. Benchmarking this example to other similar operations and ongoing adsorption testing and circuit profile sampling is required to validate the CIL modeling, especially because ore-type changes can have a significant impact on performance, as discussed in the earlier example where clays impacted the adsorption of gold.

The impact of operating parameters on the predicted solution tail are shown in Table 1. In the first three cases, the number of CIL stages was decreased, but the total carbon inventory remained the same (with higher carbon concentrations for the cases with fewer contactors). The total leach retention time was kept constant by increasing the number of leach tanks when decreasing the number of CIL stages. The model shows essentially no difference in barren solution grade with number of stages of contact, which is consistent with industry practice that has shown that six operational CIL stages are adequate to achieve low barren gold grades. However, the example with six CIL contactors has slightly higher gold inventory because of more carbon in the first contactor (highest loaded carbon grades). In the next two cases with seven CIL stages (the base design), the model clearly shows that the barren solution grades are a function of carbon concentration (inventory) because of the faster adsorption at higher carbon concentrations, but this improvement comes at a cost in terms of the gold in circuit inventory. The last case shows one of the benefits of having seven adsorption tanks when treating an ore at twice the average feed grade. Because the elution frequency usually cannot be varied significantly for an operating plant, higher loaded carbon grades are required, resulting in higher solution losses. In this case, with seven CIL stages and 20 g/L carbon in each stage, the solution loss can be maintained at 0.012 mg/L. A plant with six CIL stages would struggle under these conditions. Therefore, in designing a CIL/CIP circuit, consideration of the variability in the mill feed over the life of mine is always required.

Table 1 Modeled variation of gold in barren solution for a typical CIL plant

CIL Variable	Barren Solution Grade, mg/L
12 g/L carbon, 8 CIL contactors	0.012
13.7 g/L carbon, 7 CIL contactors	0.012
16 g/L carbon, 6 CIL contactors	0.013
20 g/L carbon, 7 CIL contactors	0.008
10 g/L carbon, 7 CIL contactors	0.019
20 g/L carbon, 7 CIL contactors, 2 g/t feed grade, same elution frequency	0.012

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Elution/Regeneration Circuits

The design of elution and reactivation circuits is also very important because the activity and gold concentration on the barren carbon both have a significant impact on the solution tails grade. Further details on the design of elution and reactivation facilities can be found in Von Becknamm and Semple (2002), Hosford and Wells (2002), and Chapter 10.12, "Carbon-in-Leach and Carbon-in-Pulp Circuit Design."

PLANT PRACTICE

The following sections present operation data from carbon adsorption circuits with varying levels of complexity.

CIC Circuits

Much of the data available on CIC circuit performance is based on heap leach solutions with high gold grades and very good upgrade ratios. The two examples that follow are somewhat different. The first is a heap leach where carbon is not regenerated/reactivated, and hence lower carbon activities result. The second example represents the growing trend with heap leach in that lower-grade ore is placed and leached, with the higher-grade ore feeding a mill, and thus the pregnant solution grades seen in the feed to CIC are very low.

In the first example, Figure 3 shows the upgrade ratio obtained for gold and silver (over two separate months of operation; the left graph is one month and the right graph is a separate month) for the CIC circuit where carbon is not regenerated/reactivated. An additional complication for this circuit is that the pregnant solution also contains variable copper, and thus the upgrade ratio is low because of high carbon movement to compensate for both the low activity and the copper on loaded carbon. The data shown in Figure 4 is the gold and silver recovery from solution over the same period as the data shown on the right side of Figure 3; the gold recovery is typically around 90%, with the barren gold solution grades ranging from 0.07 to 0.1 mg/L. The silver recovery is lower, as its adsorption is weaker than gold. This example illustrates very

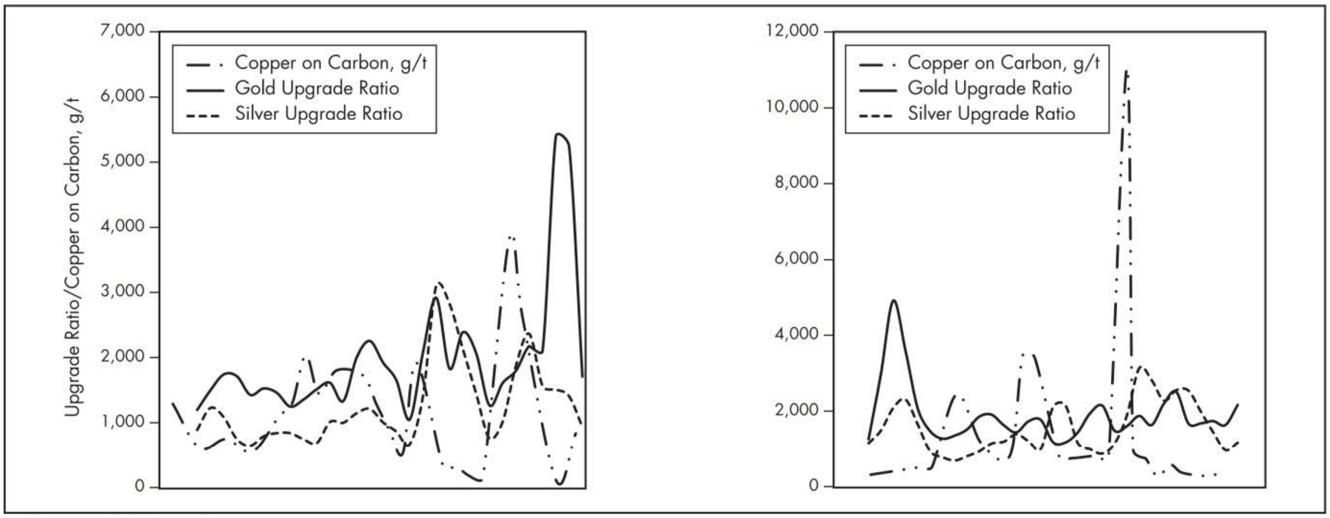

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Figure 3 CIC circuit gold and silver upgrade ratios for a circuit without carbon regeneration/reactivation and variable copper in the pregnant solution

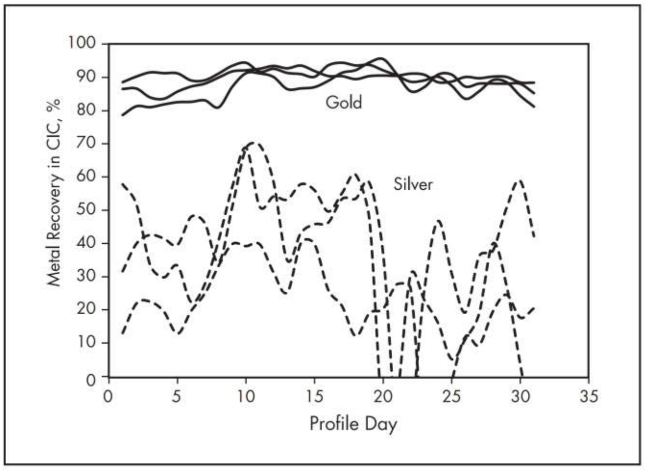

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Figure 4 Gold and silver CIC solution recoveries (three separate CIC trains) for a circuit without carbon regeneration/reactivation

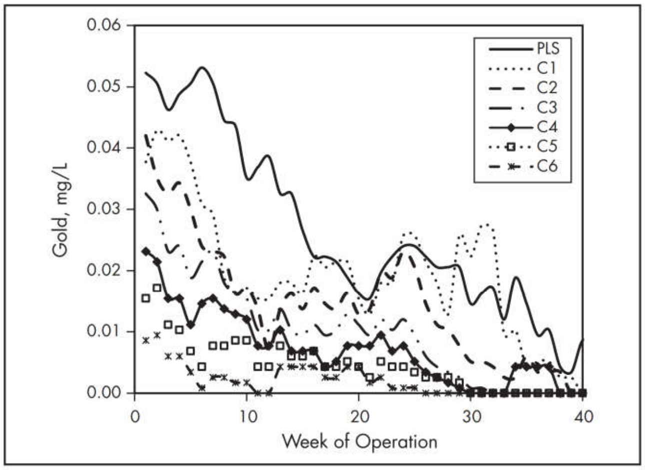

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Figure 5 Low-grade heap leach CIC solution profiles

well the impact of low carbon activity, with lower than typical CIC recoveries at lower upgrade ratios. However, other factors preclude carbon regeneration for this site, and the copper in the feed makes this circuit even more complicated to operate. Despite this fact, the circuit still recovers gold and silver, with the metal values in the barren solution being recycled to the heap leach, and hence remaining in inventory. This example highlights the robust nature of the CIC technology.

The second example is an oxide heap leach, and Figure 5 shows the CIC solution profile samples for nearly one year of operation (C1 is the gold solution concentration exiting CIC contactor 1). For this operation, the carbon activity is high because of regeneration/reactivation in the mill facility. Clearly, CIC is an exceptional technology; even as the PLS grade decreases to 0.01 mg/L gold, the adsorption efficiency remains very high. This is also demonstrated in the upgrade ratio (Figure 6), which remains high despite the decrease in PLS grade. Only the first 15 weeks are shown, as assay accuracies at <0.02 mg/L gold distort the data.

Simple CIL/CIP Circuits

Simple CIL/CIP circuits are relatively straightforward to design and operate, with significant benchmarking and historical knowledge in the industry. For example, the profiles for gold-in-solution and gold on carbon are shown in Figures 7 and 8, respectively, for an oxide mill processing around 2.8 g/t gold ore at 48% solids. The loaded carbon for the three separate surveys averages 4,170 g/t, and the final gold in solution averages 0.001–0.002 mg/L with nine stages of CIL. Note that the gold-in-solution graph shows 10 stages, because the grinding and preleach thickener contains cyanide, and hence stage 1 represents some leaching prior to the CIL circuit. This is a well-designed and operated circuit, producing high upgrade ratios and very low gold loss to tails.

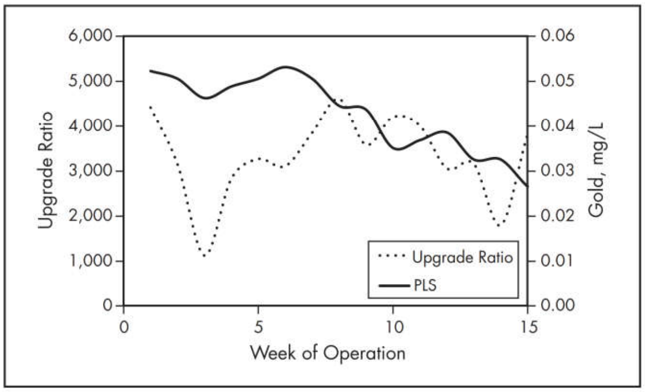

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Figure 6 Low-grade heap leach CIC gold upgrade ratio

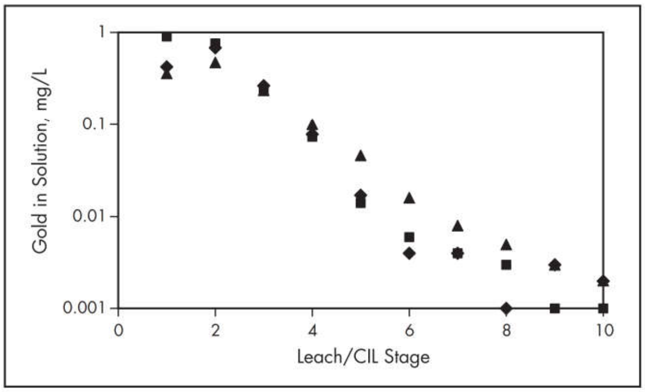

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Figure 7 Oxide mill CIL application gold in solution profiles (nine stages of CIL; different symbols represent circuit profiles taken at different times)

The graph in Figure 9 shows the gold on carbon versus gold in solution, along with the equilibrium isotherm and the modeled data for the plant (using a spreadsheet model). This demonstrates how powerful the modeling of the CIL circuits can be, and gold metallurgists should possess this capability when dealing with CIL/CIP plants. Circuit survey data can be used to continually update the model parameters and can be vital in understanding the potential impact of plant changes. For example, in one operation, CIL modeling has been used to justify the capital for an additional stage of CIL, and in another, the implementation of oxygen in the first leach tank has been used to increase the leach rate and hence gold on loaded carbon in the first carbon contactor.

High-Silver CIL/CIP

High-silver ores are not normally processed by CIL/CIP circuits as high-carbon transfers are required and adsorption is not as effective as it is with gold. Silver ore processing is more typically undertaken using countercurrent decantation or filtration for solid–liquid separation, followed by zinc cementation of the precious metals from the pregnant liquor (Merrill–Crowe). Such flow sheets are the preferred technologies when the Ag:Au ratio exceeds 10.

Profile data follows for a CIL operation during a two-month period that processes a gold ore containing higher silver. The first four tanks are leach only, and Figures 10 and 11 show the solution profiles for gold and silver, respectively. Figures 12 and 13 show the carbon profiles for gold and silver, respectively. The average gold grade feeding the first adsorption tank is 1.15 mg/L, with a maximum of 1.5 mg/L. For silver, the average and maximum grades were 8.6 mg/L and 16.7 mg/L, respectively, and hence this plant is operating close to the recommended maximum of Ag:Au = 10 for carbon adsorption. Despite this, the plant still operates well, with gold in solution tails around 0.01 mg/L and silver in tails in the range of 0.3 to 0.8 mg/L, that is, ~95% silver recovery to carbon. Obviously, maintaining good carbon activity is key to the successful operation, as the loaded metal is extremely high. Taking into account the difference in atomic mass of silver to that of gold, the maximum loadings seen in Figures 12 and 13 are equivalent to carbon loaded with 14,700 g/t gold. Another important consideration is the additional stripping and electrowinning capacity required to handle the very high total precious metal movements.

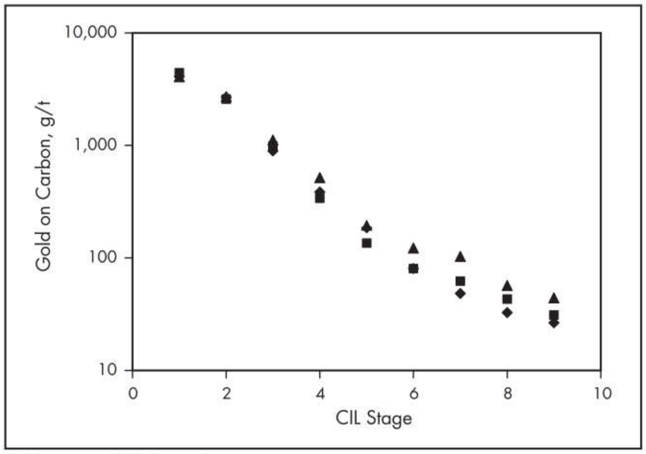

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Figure 8 Oxide mill CIL application gold on carbon profiles (nine stages of CIL)

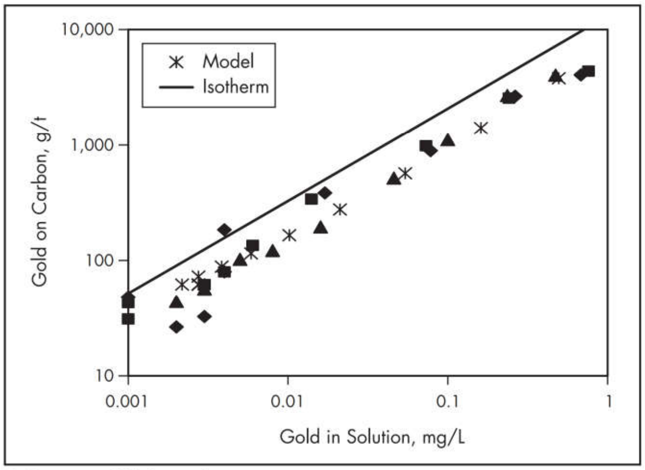

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Figure 9 Oxide mill CIL application gold loading equilibrium isotherm, plant data, and CIL model data (different symbols represent different sampling campaigns)

Because the carbon from this plant is dominantly loaded with silver, an isotherm for silver loading can be constructed from the profile data (which also include operational data from a separate window of processing high-silver ore). Figure 14 shows that the Freundlich-type model for silver loading is $2{,}066[\mathrm{Ag}]_{aq}^{0.727}$. The actual equilibrium loadings may be higher. However, these data provide an estimation of the maximum loadings obtainable in a CIL/CIP circuit for high-silver applications. In this operation, very little copper or other species affect the adsorption of metals, so when designing for CIL/CIL applications with this complexity, testing is critical to define the expected metal loadings.

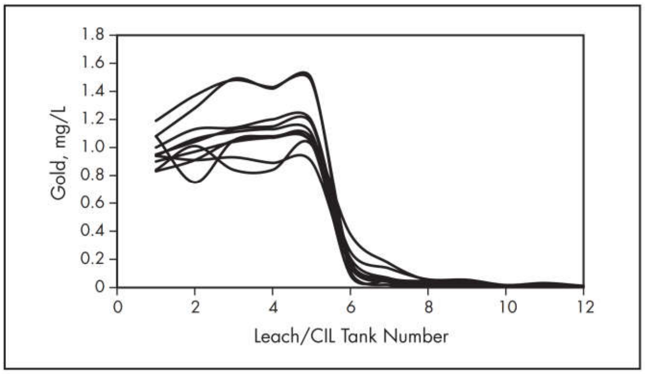

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Figure 10 High-silver mill CIL application gold in solution profiles (seven stages of CIL)

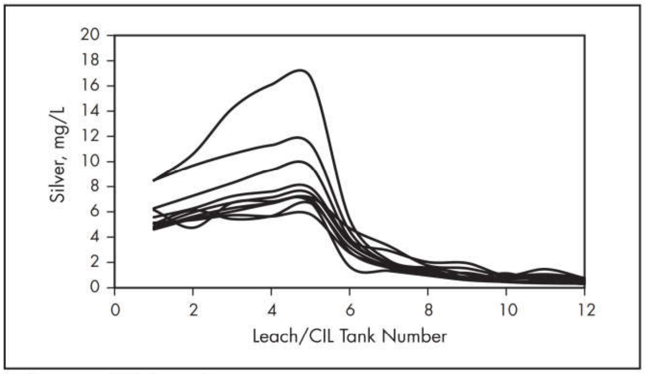

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Figure 11 High-silver mill CIL application silver in solution profiles (seven stages of CIL)

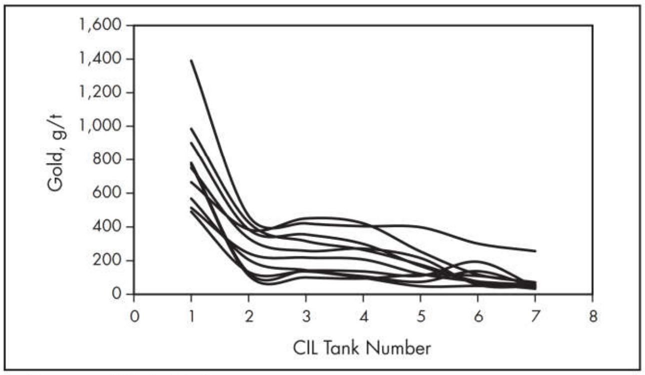

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Figure 12 High-silver mill CIL application gold on carbon profiles (seven stages of CIL)

High-Copper CIL/CIP

For facilities processing high-copper ores, the key to successful operation is to minimize the copper on loaded carbon. The best way to accomplish this is to operate the circuit with high free cyanide, which can be more difficult than anticipated, especially when the copper feed grades in the ore vary and the cyanide solubility of the copper varies as a function of variable mineralogy. A common complication is that the cyanide addition is limited by cyanide code compliance (e.g., 50 ppm weak acid dissociable [WAD] cyanide at the spigot discharge), detox capacity, or even cyanide supply constraints. This often leads to periods of operation with low free cyanide, which results in very good loading of copper.

An example of a high-copper feed is a flotation plant that leaches the cleaner scavenger tail, a higher copper/gold stream with variable copper grade and mineralogy, which is dependent on the flotation performance. Figure 15 shows circuit profile information including the copper in solution in the first carbon contactor, the copper on loaded carbon, and the free cyanide concentration. The free cyanide had been

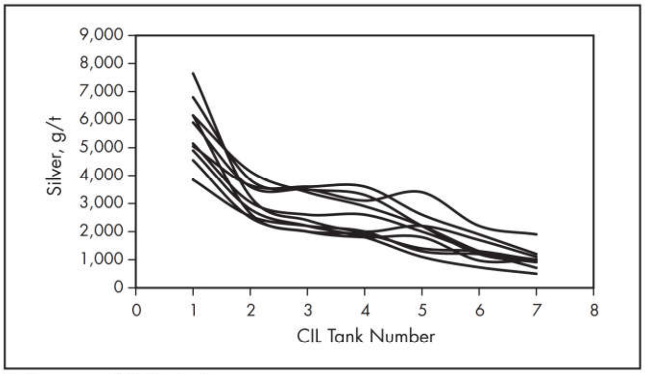

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Figure 13 High-silver mill CIL application silver on carbon profiles (seven stages of CIL)

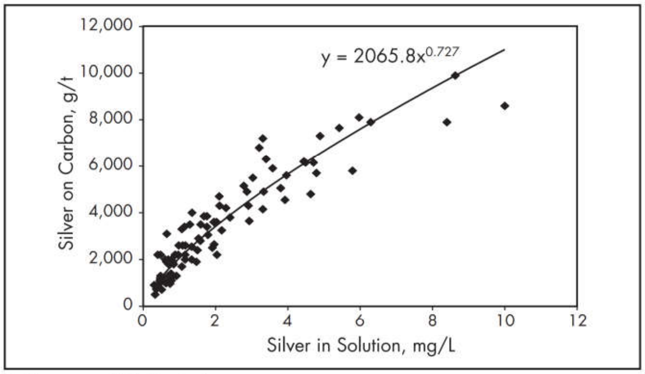

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Figure 14 High-silver mill CIL application silver loading isotherm from plant data (i.e., not at equilibrium)

measured using titration, and also calculated from the copper and a WAD cyanide measurement (using a flow injection–amperometric detection analyzer). This plant operates very well with copper loadings usually less than 1,000 g/t for copper in solution averaging around 400–500 mg/L. However, when the free cyanide drops, there is a large spike in copper loading on carbon.

Figure 16 shows the gold and silver loadings on the activated carbon during the same period. Although this data is somewhat scattered because of the variation in feed grades, the impact on gold and silver loading appears minimal because of the low overall metal loadings on carbon. The low loadings are necessary because of the presence of copper (similar to the CIC application discussed earlier) and the presence of organic flotation reagents that lead to fouling. Figure 17 shows the impact of higher copper loadings obtained during one week of operation with higher copper feed grades and limitations on cyanide addition. Clearly, significantly reduced gold and silver loadings on the carbon are obtained at the very high copper loadings.

Handling of carbon highly loaded with copper can be challenging, and the industry standard practice is to undertake a cold cyanide strip. By exposing the loaded carbon to an environment of high free cyanide, a proportion of the copper is selectively eluted over gold at the lower temperatures. The strip solution can then be treated with a SART (sulfidization–acidification–recycle–thickening) process to precipitate copper as copper sulfide and recycle the cyanide. Often, though, the strip solution is bled back into the leach circuit to make use of the high cyanide, which then relies on good CIL/CIP operation to ensure that this copper ends up going to detoxification. Any copper that goes into electrowinning can also

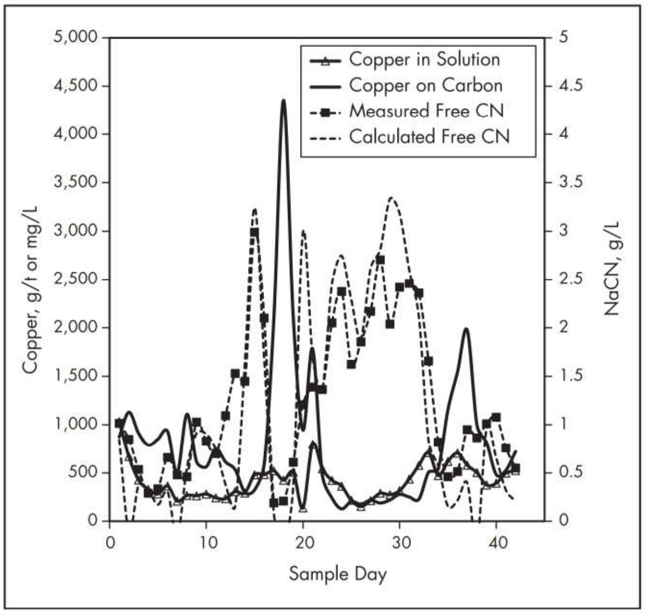

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Figure 15 High-copper CIL first-stage copper in solution and on carbon over 45 days of operation. Also shown is the measured and calculated free cyanide in the CIL stage.

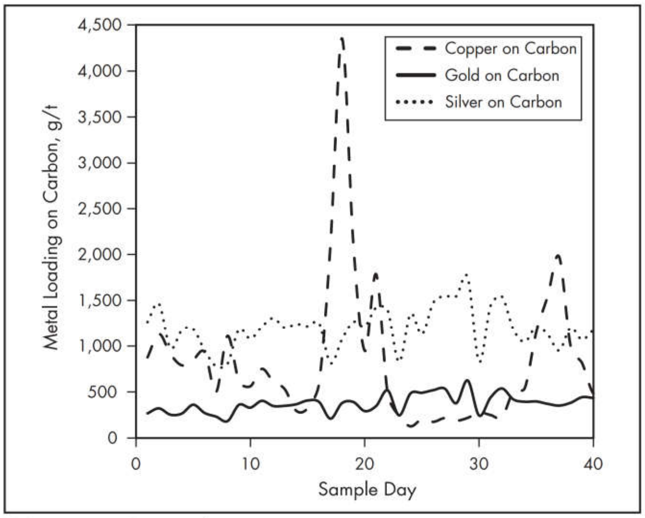

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Figure 16 High-copper CIL first-stage copper, gold, and silver on carbon over the same period of operation as shown in Figure 15

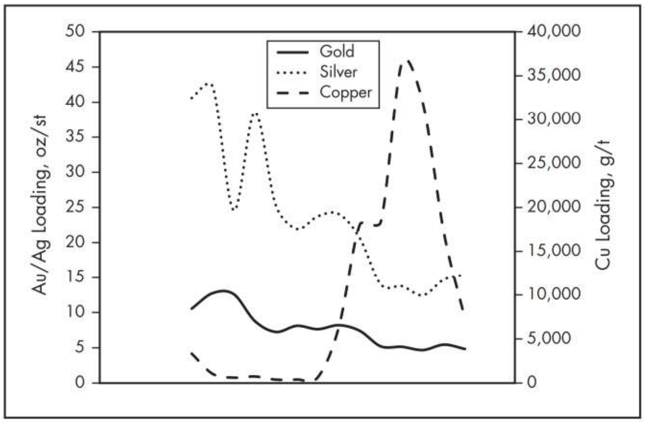

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Figure 17 High-copper CIL first-stage copper, gold, and silver on carbon over a separate period of operation with higher copper in feed

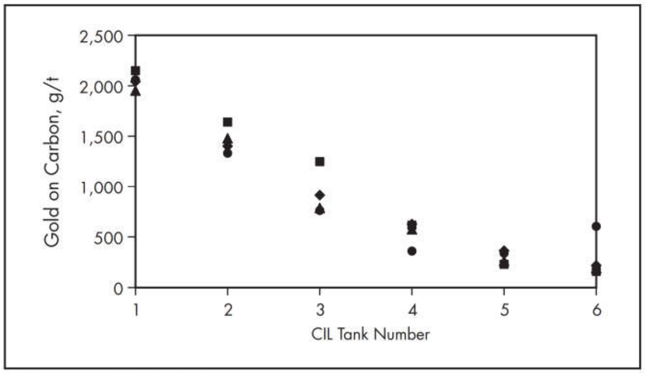

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Figure 18 Gold on carbon for a CIL plant processing preg-robbing ore (different symbols represent different sampling campaigns)

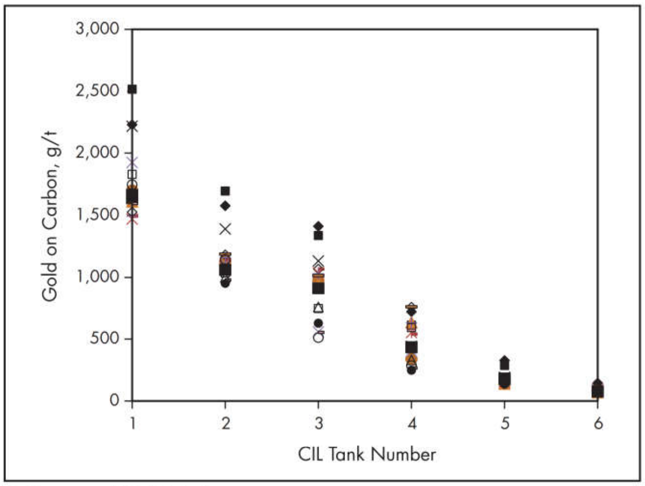

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Figure 19 Gold on carbon for a CIL plant processing a flotation concentrate (different symbols represent different sampling campaigns)

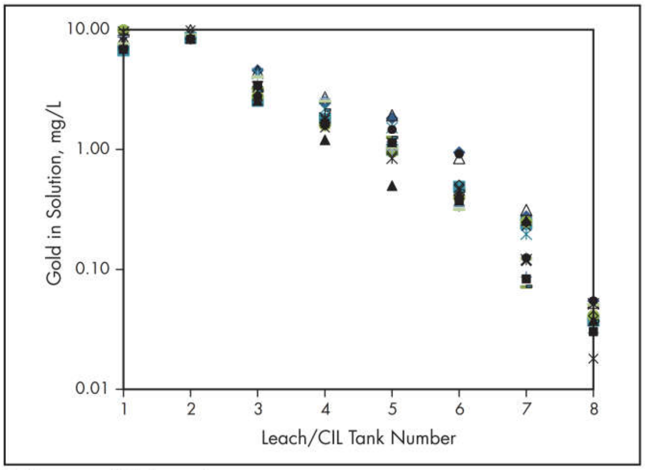

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Figure 20 Gold in solution for a CIL plant processing a flotation concentrate (different symbols represent different sampling campaigns)

be problematic, and similar to CIL/CIP, high cyanide concentrations can be adopted to minimize the plating of copper. However, some copper does report to cathode, and hence the electrowinning design needs to take this extra plated metal into account.

Preg-Robbing and High-Fouling CIL/CIP Circuits

When processing ores containing carbonaceous material that preg-robs gold from solution (adsorbs the gold cyanide complex by the same mechanism as activated carbon), an important operational strategy is to minimize the gold in solution and maximize the rate of adsorption. This is accomplished by having carbon in all the leach tanks, by reducing the loading of gold on carbon (remembering that according to the isotherm, gold on carbon is a function of gold in solution), and by operating at higher carbon populations. Consequently, the upgrade ratios will be lower than for conventional circuits. Figure 18 shows the gold-on-carbon profiles for an operation treating mildly preg-robbing ore for which the average gold feed grade was 4.6 g/t gold and the average loaded carbon was 2,080 g/t.

The operation of CIL/CIP circuits treating either flotation tails or concentrates, which usually result in high fouling of the carbon, is very similar to preg-robbing circuits in that carbon must be transferred faster, with lower loadings of gold. This is because both the equilibrium isotherm and the carbon adsorption rate (activity) are impacted by the organic reagents (collectors and frothers). The circuit profiles for a flotation concentrate leach circuit for a four-month period are shown in Figure 19 (gold on carbon) and Figure 20 (gold in solution). The circuit consists of two leach and six adsorption tanks, and the average gold in solution feeding the first adsorption tank was 10.3 mg/L, producing a loading of 1,757 g/t gold on average, that is, an average upgrade ratio of only 171 from solution. The tails solution grades achieved average 0.04 mg/L, representing 99.6% gold recovery from solution.

CONCLUSIONS

Carbon adsorption is a very robust technology for recovering gold from cyanide leach solutions, whether it be via CIP, CIL, or CIC processes. This has led to carbon adsorption–based processes being the dominant technology in gold hydrometallurgy, with the traditional Merrill–Crowe process usually adopted only for circuits with very high silver (Ag:Au > 10). The implementation of CIP/CIC/CIL circuits for simple gold ores is relatively straightforward, with significant operating data and modeling available to inform on this application. For complex ores, often lower gold loadings need to be targeted to account for either fouling or co-loading of copper and/or silver. For preg-robbing ores, lower gold loadings result from the requirement to minimize the dissolved gold in solution. The examples provided for treating complex ores provide a basis for understanding the potential impact of these more complex feeds, which are the norm for modern gold processing facilities. These complex ores require significantly more metallurgical work to define the carbon adsorption behavior, and detailed modeling to design the CIL/CIP circuit. Despite the challenging applications, carbon adsorption is an exceptional technology.

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