

ACTIVATED CARBON IN GOLD RECOVERY

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1. INTRODUCTION

This article serves to discuss the fundamental aspects of gold recovery utilizing the Carbon-in-Pulp or Carbon-in-Leach processes. The purpose is to describe in simple terms what activated carbon is all about and how it adsorbs gold. The understanding of the mechanism of gold adsorption is important because the CIP/CIL processes work as a result of the gold adsorption mechanism, which is a chemical occurrence. Factors that affect the adsorption of gold are discussed. Finally, performance monitoring methods that help control the operation of the CIP/CIL process are discussed.

2. WHAT IS ACTIVATED CARBON?

"Activated Carbon" is a generic term for a family of highly porous carbonaceous materials that cannot be defined by a structural formula, or by chemical analysis. In other words, a piece of carbon with millions of tiny interlocking holes (called pores) is called activated carbon. Under a microscope, activated carbon looks like a sponge. The millions of tiny interlocking holes occupy space within the carbon and thus activated carbon has a very high internal surface area. Typical activated carbons used in the Carbon-in-Pulp (CIP) and Carbon-in-Leach (CIL) processes have surface areas of about 1000 m²/g i.e. one gram of activated carbon (the amount of which will occupy the same space as the end of a person's thumb) has the same surface area as two football fields.

The high surface area is contained in the millions of pores of varying sizes, these being defined by the following groups:

Macropores (500 to 2000 Å in diameter) these are the large pores that run from the surface of the activated carbon into the interior. The macropores allow for the rapid movement of adsorbates (species that will be adsorbed by the carbon, e.g. gold) into the activated carbon granules.

Mesopores (100 Å to 500 Å) these are the pores that branch off the macropores that serve to allow the adsorbates to leave the macropores

Micropores (8 to 100 Å) which are of the right size to allow the adsorbates to be strongly adsorbed by activated carbon. These pores generally occupy 95 % of the total internal surface area of activated carbon. It is within the micropores that adsorption takes place, however the meso and macropores are important because they facilitate the rapid transport of the adsorbates into the activated carbon.

* Note Å is an angstrom. One angstrom is 0.00000001 cm or 10⁻⁹ cm.

Activated carbon is essentially carbon, it is inert, and so it carries no charge (unlike Na^+ Cl^- ; salt). Since activated carbon carries no charge, its internal surface area is also neutral, therefore activated carbon will adsorb only neutral species. As a result activated carbon will adsorb any neutral species from water, industrial solutions and from gasses, leaving behind the charged species such as Na^+ and Cl^- .

The applications of activated carbon are wide spread, examples of some are as follows:

- Removal of organic species from industrial effluents.
- Removal of organic contaminants (and chloride from portable water).
- Recovery of precious metals like Gold.
- Removal of contaminants in gas, gas masks.
- Medicinal – removal of certain species in human digestive system.
- As a carrier for impregnates.

3. MANUFACTURING OF ACTIVATED CARBON

Activated carbon is manufactured from carbonaceous raw materials. Examples are:

- Coal: Peat, Lignite, Bituminous coal, Anthracite.
- Nut shells: Coconut, Macadamia.
- Pips: Apricot, Peach, Olive.
- Wood.
- Cellulose.
- Heavy oil.
- Bones.

The requirement is that raw materials are available in sufficient quantities to support commercial production.

Typical carbon content of some raw materials are:

Material	Carbon Content (%)
Wood	40
Coconut shell	40
Lignite	60
Bituminous coal	75
Anthracite	90

There are two methods in which activated carbon is produced:

1. Chemical

In which the raw material is mixed with acids such as Phosphoric or Sulphuric acid, dried then heated up to 650 °C. In the Calcination step the impregnated chemicals dehydrate the raw material resulting in charring and creation of a porous structure. Chemical activation is used most often in manufacturing activated carbon from wood.

2. Physical (thermal)

In which the raw material is firstly charred in the carbonization step. The char is then heated at elevated temperatures in the presence of steam to create activated carbon.

In gold recovery applications, activated carbon manufactured by Thermal activation is used. This process will be discussed in more detail.

There are a number of steps in the production of activated carbon:

Preparation of raw material

The raw material may be collected, cut and cleaned as the preparation step. This applies to nut shells, pips and wood.

In the case of coal based raw materials, the raw material is not uniform in quality and therefore is milled, mixed with a binder (pitch for example) and briquetted or extruded under pressure to prepare a dense carbon rich raw material. The briquettes would normally be crushed and screened prior to carbonization.

Carbonization

Carbonization is the step that produces char. In this step, the raw materials are indirectly heated up to 700 °C to drive off the volatile organic contaminants and dehydrate the raw material. This is carried out in an inert atmosphere, normally created by the volatile species.

This produces a char product with a fixed carbon content of 80 % or more. The internal surface area of char is 10 m²/g or lower.

Activation

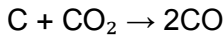
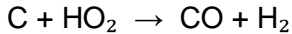
The Char produced in the carbonization step is crushed and sized to form the precursor which is fed into a kiln in where the char is activated using a steam rich atmosphere.

The char is directly heated inside the kiln using a flue gas into which steam is injected. Rotary kilns (common for coconut shell based carbon), fluidised bed kilns and multi hearth kilns are the most common kilns used for the manufacture of coal based activated carbon.

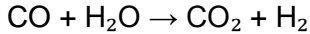
The temperature at which activation is carried out is between 800 to 1000 °C. In this step the steam reacts with the carbon in the char to create the high internal surface area of ± 1000 m²/g.

The activation step typically takes 24 hours and consumes 1 kg steam / kg carbon/ hour.

The reaction between steam and carbon is called the water gas reaction:



And the secondary reaction:



The water gas reaction was commonly used to produce Town gas ($\text{CO} + \text{H}_2$) by reacting coal with steam, before the advent of natural gas.

The water gas reaction is endothermic. This means that energy has to be put into cause the reaction. Unlike the reaction between Carbon and Oxygen, which gives off heat (exothermic).

This allows the activation step to be accurately controlled, allowing for preferential etching of the internal carbon structure (carbon inside the granules) and the formation of the large internal surface area and creation of the pore structure.

The rate of the water gas reaction is temperature dependent.

During carbonization and activation, the carbon structure is also changed. As the temperature increases polymerisation of the large chain aliphatic and aromatic molecules occurs, forming a system of planar condensed benzene - ring molecules. This occurs up to 400°C.

- Between 400 and 700°C, these condensed ring systems grow. The peripheral carbon atoms are attached to hydrogen atoms and hydro-carbon groups, and have high electrical resistivity.
- Between 700 and 800°C, hydrogen and hydrocarbon groups are expelled leaving small crystallites housing a graphic like structure. The resistivity of the product is reduced, becoming electrically semi conductive.

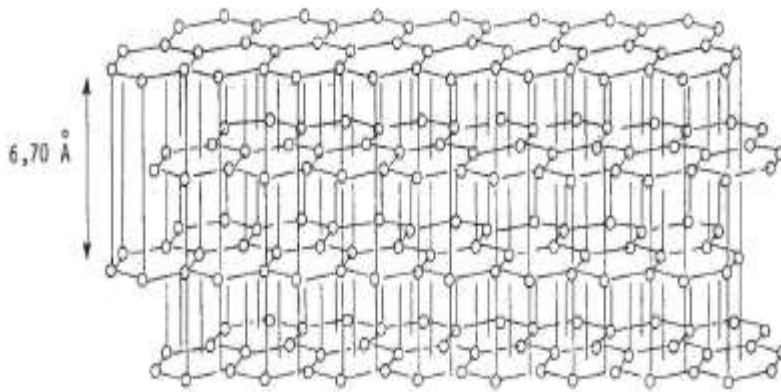


Fig 1: Schematic representation of the structure of graphite. The circles denote the positions of carbon atoms, whereas the horizontal lines represent carbon-to-carbon bonds.

From: GJ McDougall, Carbon School 1985 – Lecture 2.

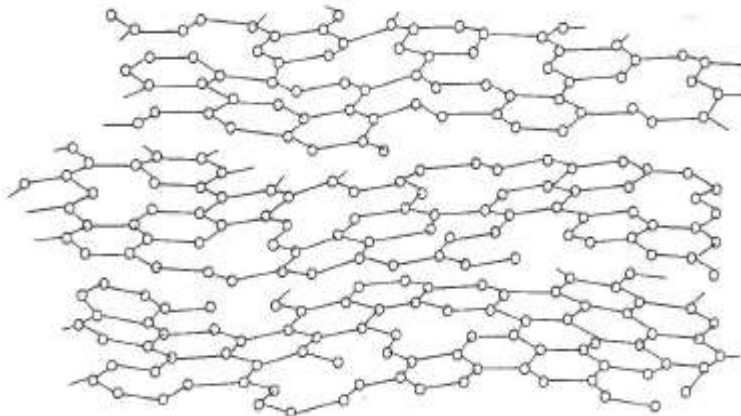


Fig 2: Schematic representation of the proposed structure of activated carbon. Oxygen-containing organic functional groups are located at the edges of broken graphitic ring systems.

From: GJ McDougall, Carbon School 1985 – Lecture 2.

4. CHARACTERISTICS OF ACTIVATED CARBON

During manufacturing of activated carbon, the basic structure of the raw material is not reformed, (except for coal based carbon). The characteristics of the activated carbon product is thus dependent on the raw material utilized (and for coal, the reformation process).

A hard, dense raw material, like coconut shell, produces a hard and dense activated carbon. A soft less dense raw material like wood, produces an activated carbon with a lower density.

The pore structure of the activated carbon is also dependent on the raw material.

Coconut shell based activated carbon has a pore structure forming micro-pores, whereas wood based activated carbon has a pore structure forming larger pores due to the open structure of wood:

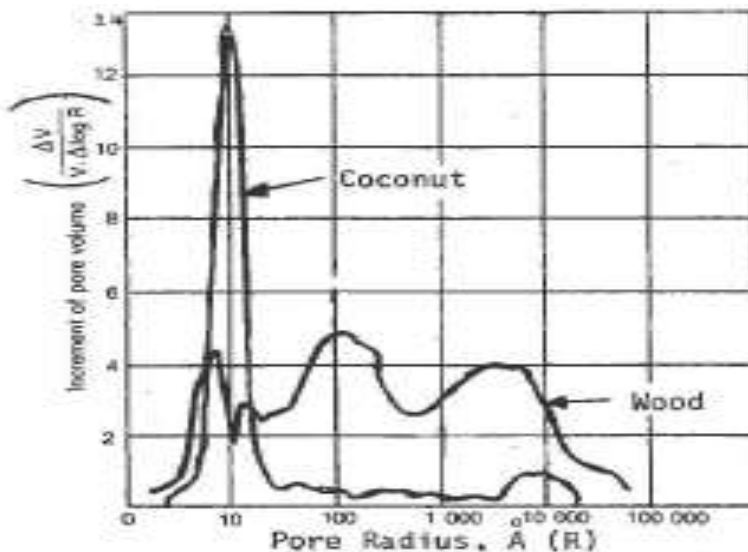


Fig 3: Pore-size distribution data for (a) a typical thermally activated coconut-shell based activated carbon and (b) a typical chemically activated wood-based product. (From CJ McDougall – Carbon School, 1985, Lecture nr 2).

Coal based activated carbon, due to the reformation of finally crushed coal mixed with a pitch (e.g.) binder, has a pore structure defined by reformation process consisting of micro, meso and macro pores:

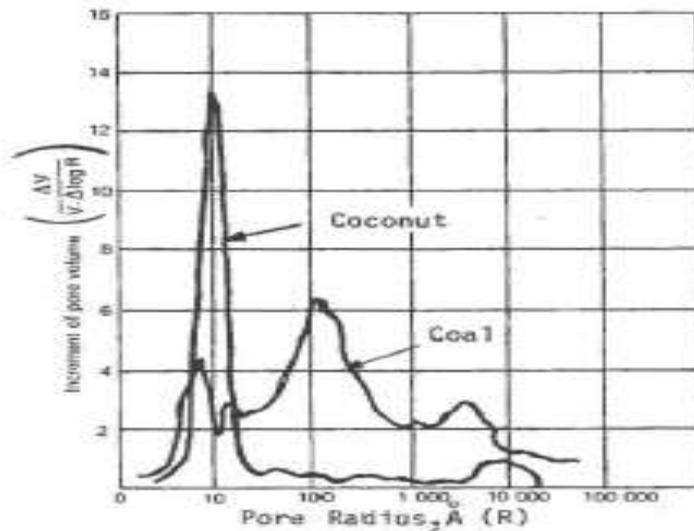


Figure 4: Pore-size distribution data for a typical thermally activated coal-based activated carbon and a coconut carbon.
(From G.J. McDougall, Carbon School, 1985, Lecture 2).

The application in which the various activated carbon types are used is based on their key characteristics:

- Coconut shell based: adsorption of smaller molecules from gas and liquids. In gas masks, solvent recovery, in cigarettes and for gold recovery.
- Wood based; adsorption of large usually coloured organics from industrial streams.
- Coal based: adsorption of a range of organic molecules that range in size. Most commonly used in portable water treatment and waste water treatment.

In the gold recovery industry, activated carbon from a number of precursors has been used. Due to the nature of the in-pulp process, the following characteristics are important:

- High affinity towards gold – kinetic activity and equilibrium loading.
- Hard, resistant to abrasion.
- Density, suited to mixing in pulp.
- Source material supply not limiting.

Coconut shell oil is one of the global vegetable oils, about 6 million tons per year is produced. This is 2.5 % of the annual world vegetable oil supply. Coconut shells are a waste product, (consisting of about 15 % of coconut). Considering about 60 million tons of coconuts are harvested per year, coconut shells are available on an industrial scale.

5. ADSORPTION

Adsorption is the term used to describe the tendency of atoms / molecules in gas or liquid phases to adhere to a solid surface. It is the separation of the species being adsorbed, the adsorbate, from one phase and concentrating it onto the surface of a solid phase, called the adsorbent.

There are two types of adsorption:

- Physical adsorption, which is caused mainly by Van der Waals forces and electrostatic forces between the adsorbate and atoms which compose the surface of the adsorbent. Van der Waals forces are weak short range attractive forces between uncharged molecules arising from the interaction of electric dipole moments. There is no reaction between the adsorbate and adsorbent. Physical adsorption is reversible.
- Chemical adsorption, in which there is a reaction between the adsorbate and surface atoms of the adsorbent (bond formations). Chemical adsorption is not reversible.

Activated carbon adsorbs by physical adsorption. In physical adsorption the adsorption forces are weak. The adsorbents are characterized by surface area and polarity. A large surface area provides for a large adsorption capacity, which is encompassed in pores inside the adsorbents.

Surface polarity corresponds to affinity to polar substances (such as water). Polar adsorbents are called hydrophilic (water liking). Non-polar adsorbents are called hydrophobic (water hating). Activated carbon is a non-polar adsorbent and would have affinity hydrophobic species, such as hydrocarbons, therefore activated carbons would selectively remove hydrocarbon from water. Activated carbon would also selectively adsorb some species over others. Adsorption is equilibrium and kinetics dependent.

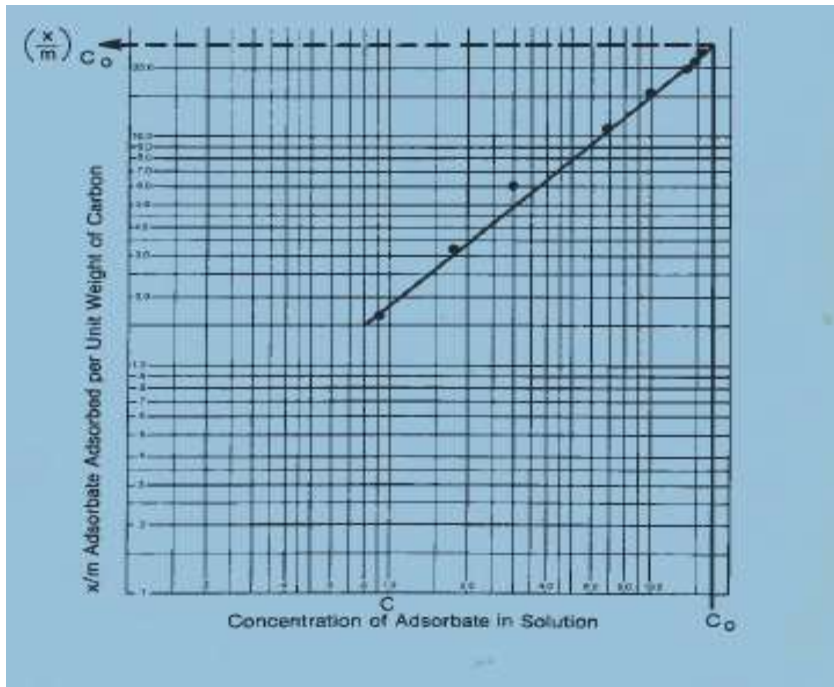
Equilibrium adsorption: At equilibrium there is a defined distribution of adsorbate between liquid and solid surface.

Equilibrium adsorption is usually described through isotherms; the amount of adsorbate adsorbed onto the adsorbent as a function of concentration in liquid. A number of isotherms models have been developed. The one we are most familiar is the Freundlich isotherm.

$$x/m = k^{1/n}$$

k and n are constants, x/m is the amount of adsorbate per unit weight of adsorbent is equilibrium with a solution concentration C.

The slope is $1/n$, and the intercept of adsorbate concentration of 1 is k. The interpolation of the line to intersect C_0 , the original concentration of the adsorbate provides the equilibrium loading of adsorbate. The slope is an indication of the affinity activated carbon has for the adsorbate. The steeper the slope - the greater the affinity.



From: "Schuliger, Wyne G, Chapter 2 in Cheremisinoff, Paul N - Carbon Adsorption Handbook, Ann Arbor Science, 1978".

There are a number of factors that affect adsorption equilibrium:

- Surface area of the carbon.
- Affinity the activated carbon has for the adsorbate.
- Competitive adsorbates.
- Concentration of adsorbate.
- Temperature.
- pH.

Adsorption kinetics:

This is the rate of adsorption, there are three steps:

- Diffusion through the liquid film (boundary layer), that surrounds the carbon granules (Film diffusion).
- Diffusion of the adsorbate within the pores of carbon (Pore diffusion).
- Adsorption onto the internal surface of carbon (Surface diffusion).

Film diffusion is regarded as rate limiting step. It is defined by the expression:

$$R = k_f A(C - C^y)$$

“R” is the mass transfer rate through film

“ k_f ” is the mass coefficient.

“A” is the external area of the carbon particles.

“C” is the concentration of adsorbate in the bulk solution.

“ C^y ” is the concentration of the adsorbate of the solution carbon interface. This is zero as adsorption is not limiting.

In the adsorption of gold cyanide and other adsorbates by activated carbon in CIP and CIL is slow, loading is well below equilibrium loading. Extraction efficiency in CIP and CIL plants is basically governed by kinetics of adsorption.

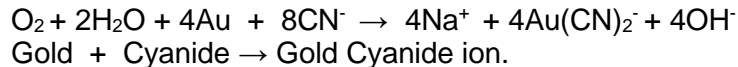
Applying the above expression to the CIP/CIL application, the factors that effect kinetics for adsorption of gold by activated carbon are:

- k_f the mass transfer coefficient defines the intensity of mixing, the greater the agitation intensity, the faster the rate.
- The increase in intensity narrows the boundary layer thickness. Increasing viscosity and density would slow the rate.
- A – Carbon particle size and concentration have a direct impact. Increasing carbon concentration and decreasing particle size increases the rate.
- C – Increasing gold concentration increases the rate.

6. THE MECHANISM FOR GOLD ADSORPTION

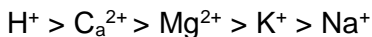
Gold is a noble metal, it prefers to exist in its natural state as gold metal. Very few metals are noble metals and noble metals are by nature unreactive. Cyanide is one of the few chemicals that will react with gold. In metallurgical applications, gold recovered is generally present in low grades thus must be "concentrated up" to an extent where it may be smelted into a bar. Since practically all gold reserves are very low (up to 20 g/t ore) the gold must be concentrated up using methods that rely on a change of phase. It is much easier to "concentrate up" gold from the solution phase than from the solid phase. Activated carbon is an adsorbent that increases the concentration of gold in the solution phase. For example, an ore containing 3 g/t is leached, mixed with carbon, which loads to 3 000 g/t, a concentration up of 1 000 times.

Initially the gold is leached using cyanide, lime and oxygen. The mechanism for leaching of gold is complex and the exact mechanism is subject to argument, however, from the activated carbon point of view, the dissolution of gold from the ore results in gold present in water as the gold cyanide ion approximated as follows:



The gold cyanide ion in water prefers to be a neutral species and thus the negative charge will be countered by any positive ion such as Ca^{2+} , Mg^{2+} , H^+ , Na^+ , K^+ , etc.

The nature of the cation present has a marked effect on the adsorption capacity of gold.



The stability of the ion pair between the Metal n^+ and gold cyanide governs the selectivity for calcium, the gold cyanide ion joins with calcium to form a calcium gold cyanide ion pair:



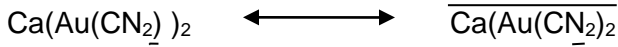
The ion pair is formed when the calcium ion and the gold cyanide ion are combined to form an IONIC BOND, the two ions having joined together forming a new chemical species without changing each other. In other words, the ions of opposite charge balance each other to form a neutral species. If the ion pair is formed under certain conditions, other conditions can easily break the ion pair. Since conditions perfect for ion pair formation do not exist under real conditions, ion pair formation and breaking occurs continuously.

An equilibrium is formed, at a given time a certain percentage of gold exists as the gold cyanide ion, and the rest is present as the ion pair. Even if 99 % of the gold is present in the ion pair and 1 % as the gold cyanide ion, an equilibrium still exists, but the conditions favour ion pair formation.

As discussed before, activated carbon has a large internal surface area which has no charge thus only neutral species will be adsorbed by activated carbon.

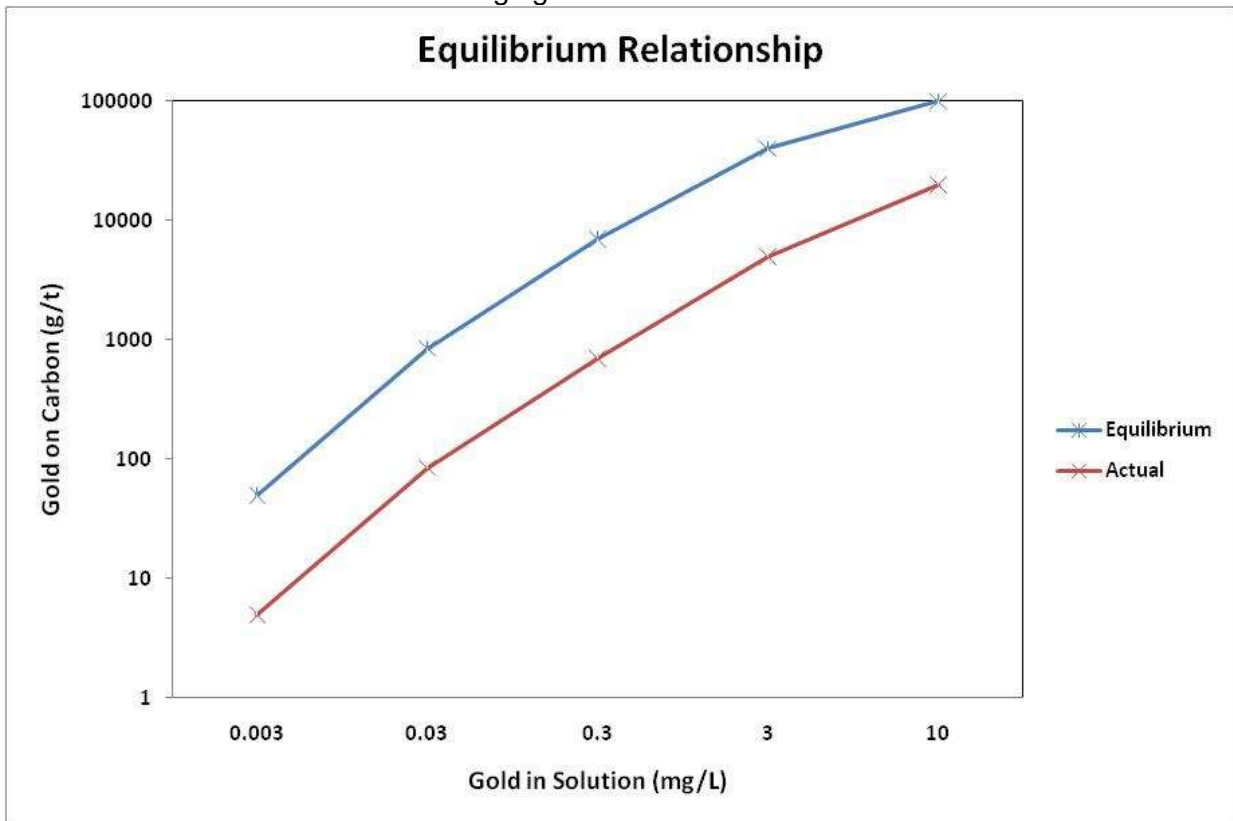
The ion pair is a neutral species and this will be adsorbed, while the gold cyanide ion is charged, so activated carbon will not adsorb it.

The adsorption of the gold ion pair onto the activated carbon surface is expressed as:



Since there is no reaction between the gold ion pair and the surface of carbon, the extent of adsorption is dependent on external factors. Perfect conditions do not occur in reality for adsorption, so an equilibrium is formed.

The factor that most influences the CIP/CIL process is the concentration of gold in solution. This is shown in the following figure.



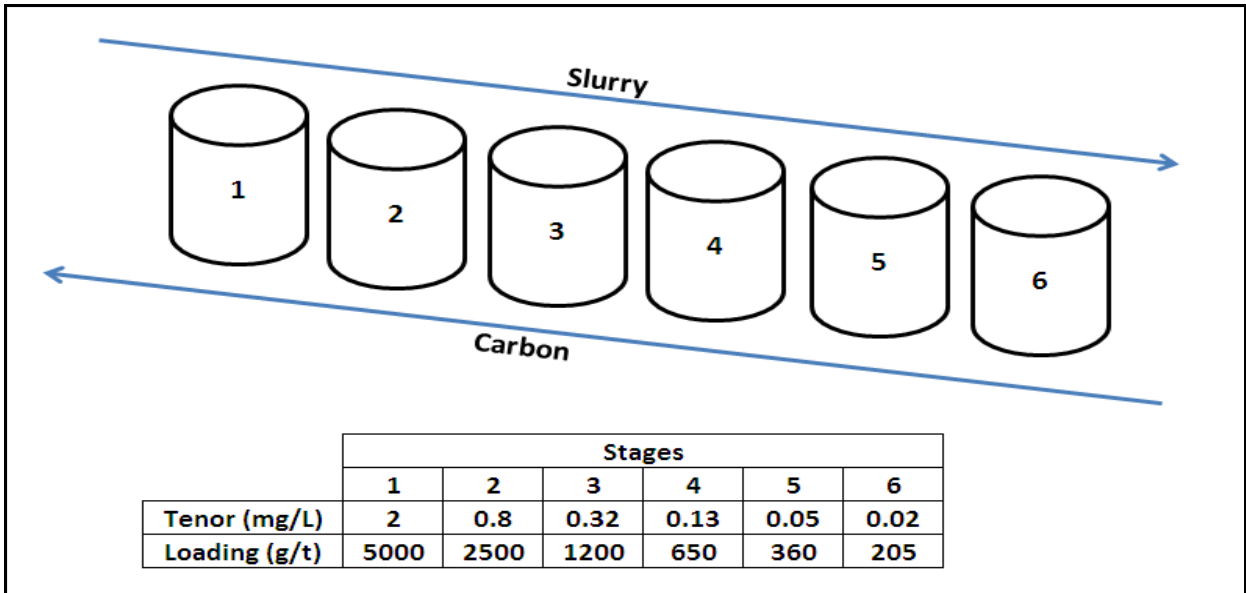
The figure shows that the higher the concentration of gold in solution, the higher will be the amount of gold adsorbed onto activated carbon. For example, if a contactor has a certain volume of pulp with a gold tenor of 2 mg/l of gold in solution, when activated carbon is added and allowed to mix indefinitely, the activated carbon will adsorb the gold to loadings of approximately 12 000 g/t carbon. The amount of gold left in solution is 0,2 mg/l. No matter how long the mixing is allowed to continue, no more gold will be adsorbed as the gold in solution and gold on carbon are at equilibrium. This equilibrium can only be disrupted when the loaded carbon is removed from the contactor and replaced by fresh carbon. The fresh carbon will again adsorb gold from the solution loading to 3000 g/t, with the corresponding gold in solution value being 0,02 mg/l, as

obtained before. Since the gold in solution before the second contact was lower than that before the first contact, the gold on carbon and gold in solution values at equilibrium are also lower. The whole process can be repeated until the final gold in solution is very low (in this case 0,003 mg/l). The gold loaded onto carbon to achieve this is only 30 g/t. Thus, two important points are noteworthy:

- To ensure low gold in tails after gold recovery utilizing carbon, the gold loaded onto carbon must also be low.
- To ensure a cost effective process, high gold on carbon values must be obtained. To achieve this the gold in solution must also be high, resulting in high solution gold in tails after gold recovery.

If we put those two factors in series, move the carbon counter current to the pulp up a series of contactors, then we have a CIP plant. This is demonstrated in Figure 2, with gold on carbon and gold in solution for each contactor given below the figure.

Feed = 5 mg/l



The results show that the carbon adsorbs gold as it moves up the series of contactors, progressively adsorbing more gold, while the gold values in solution get progressively lower down the series of contactors.

7. FACTORS INFLUENCING GOLD ADSORPTION ONTO ACTIVATED CARBON

The adsorption of gold is affected by a number of external factors that affect both equilibrium and kinetic adsorption. The design and operation of an adsorption circuit will be governed by these factors:

- Mixing efficiency.
- Pulp density.
- Particle size of carbon.
- Temperature.
- Cyanide concentration.
- pH.
- Ionic strength.
- Gold tenor.
- Contact time.
- Organic poisons.
- Inorganic poisons.
- Quality of activated carbon
 - Carbon activity.
 - Elution grade.

7.1. MIXING EFFICIENCY AND PULP DENSITY (IN CIP / CIL)

An increase in mixing efficiency increases the turbulence of liquid around the carbon granules. This reduces the liquid boundary layer surrounding the carbon granules and allows for faster adsorption.

In order to maximize gold adsorption, the carbon must be evenly distributed throughout the concentrate. This is achieved by controlling pulp density. The density of wet carbon is in the region of 1.3 to 1.5 t/m³, thus the density of the pulp must be similar in order to suspend and distribute the carbon evenly. If the pulp density is too low, then the carbon will sink to the bottom of the contactor, if the pulp density of the pulp is too high, the carbon will float. In both cases insufficient mixing will occur, resulting in a lower gold recovery.

Activated carbon has a bulk density of 0.500 g/ml and a pore volume of 0.8 ml/g. If the pore volume is filled with water having a density of 1 g/ml and add the two values, the density of wet carbon is typically 1.3 g/ml.

7.2. PARTICLE SIZE OF CARBON

The smaller the size of granules of activated carbon, the faster the adsorption of gold by the carbon. However, the smaller the carbon granular size the harder it is to screen the carbon from the pulp, thus the particle size of activated carbon used in CIL and CIP plants is a balance between, screening efficiency and gold adsorption (and the thickness of the coconut shell). The size ranges of activated carbon commonly used are:

8/16 # ASTM (1.18 mm to 2.36 mm).

6/16 # ASTM (1.18 mm to 3.35 mm).

6/12 # ASTM (1.70 mm to 3.35 mm).

7.3. ORGANIC POISONS

Since activated carbon will adsorb any neutrally charged species, many organic species will be readily adsorbed in competition with the calcium gold cyanide ion pair. Organic species originate from:

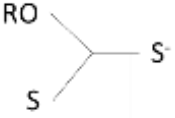
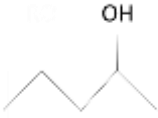
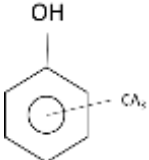
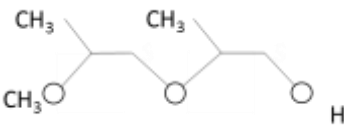
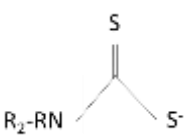
- Flotation reagents from an upstream flotation plant.
- Oils, degreasers etc from leaking glands, washing of equipment, trackless mining oil deposits, etc.
- Humic and Fulvic acids originating from plant material (vegetation, wood etc).
- Various organics originating from water used in the plant (e.g. river water, dam return water and sewage water etc.).

Organic species compete directly with gold. A small amount of organics can significantly depress gold adsorption as the activated carbon concentrates the organic species on its surface, and behaves as if there is a significant amount of organic species in the solution.

The table below is a collation of some of the results of a test program to evaluate the gold adsorption kinetic activity of activated carbon in the presence of a variety of organics that are likely to be present in a CIP or CIL circuit. Some typical waters were also tested. The comparisons are on the basis of depression of activity and shows that certain organic species such as flotation reagents suppress the carbon activity significantly. The data also demonstrates that the choice of water to be used can have an adverse impact on gold adsorption.

Activity of Activated carbon in the presence of a suite of organic species

(ACIX procedure, with 100 mg/l organic concentration)

Organic Species	Molecular Structure	% Depressant
Carbon		0
Xanthate (collector) SNBX (Na normal Butyl X) SNPX (Na normal Propyl X)		61 44
MIBC (frother)		24
Starch Depressant		41
Crysilic Acid (frother)		42
Polypropylene glycol (frother)		41
DTC (Propyl) – Collector		9
Turbine oil		19
Transmission oil		15
Engine oil		30
Hydraulic oil		11
Polyacylamide (magnafloc)		0
CIP Feed water		20 to 30
Return dam water		16 to 32
Domestic water		10 to 15
Sewerage water		16
River water		25

The selectivity activated carbon has for organics is variable, some organics are more strongly adsorbed than others. pH also has an impact on selectivity on some organic species. Organic bases and acids dissociate at certain pH, increasing charge density therefore being less strongly adsorbed. Hence some organic species are removed during strong acid (acid washing) and strong basic (elution) conditions in a gold plant.

Activated carbon has a strong affinity for organic compounds, and is able to adsorb organics more than its mass (100 % wt/wt). It is important to control the fouling of activated carbon by organics as the selectivity for gold could be reduced to a level that significant gold loss would occur. Organic foulants are removed by thermal regeneration.

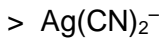
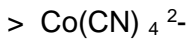
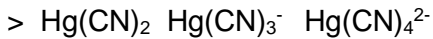
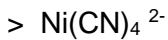
7.4. INORGANIC POISONS

These fall into two categories:

- Those adsorbed by the carbon.
- Scale formation on activated carbon.

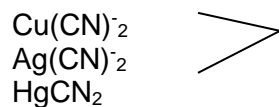
7.4.1. Adsorbed inorganic poisons

The only significant inorganic poisons that affect carbon by adsorption are base metal cyanides. Cyanide reacts with any base metal in a similar way it reacts with gold. Base metals originate from the ore itself or from process stages such as milling (ball attrition). The most common base metal cyanides are as follows:

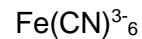
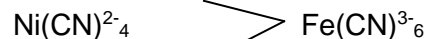


Since activated carbon will not adsorb any charged species e.g. all the base metal cyanides depicted above must be adsorbed as neutral species. Since gold cyanide forms the calcium gold cyanide ion pair, the base metal cyanides will do likewise. The stability of the ion pairs formed is heavily dependent on the charge of the anion, the lower the charge the more stable the ion pair thus the greater likelihood of adsorption by activated carbon. Thus the base metals can be ranked in order of adsorption onto the activated carbon:

STRONGLY ADSORBED



WEAKLY ADSORBED



$\text{Co}(\text{CN})_4^{2-}$ is not adsorbed, as it has a charge density too high to form an ion pair.

Copper has unique characteristics in that the Copper Cyanide complex formation is pH dependent (in the presence of excess cyanide):

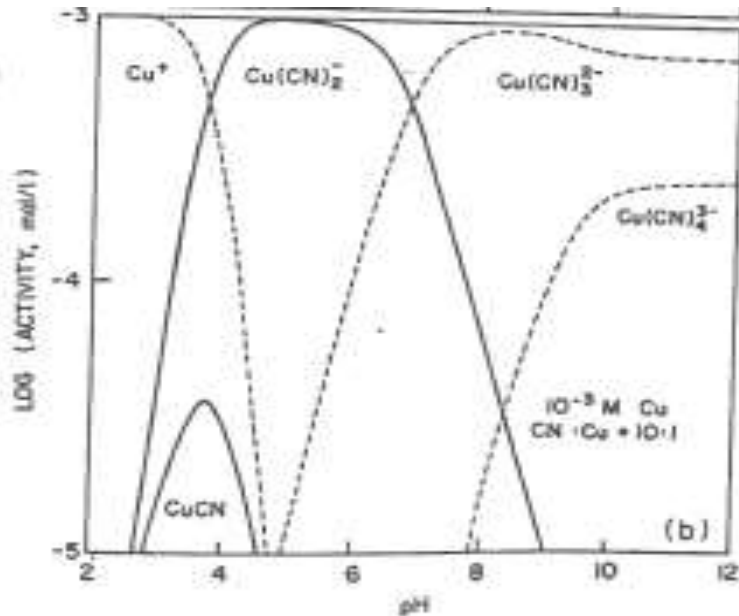


Fig 6: The distribution of the cyano complexes of Cu(I) as a function of pH. From: Minerals & Metallurgical Processing. Ibrado and Fuerstenau, 1989.

The above figure shows the distribution of the cyano copper complexes of Cu(I) as a function of pH, Cu(CN)_2^- forms strong ion pairs and so is adsorbed by activated carbon. Cu(CN)_3^{2-} and Cu(CN)_4^{3-} have high charge density so will adsorb onto carbon to a lesser degree or not at all. In practice, the presence of copper in the three complexes may fluctuate with pH. It is not uncommon to find strong adsorption of Copper by Carbon at a pH of 10.5. Thus, if large amounts of copper are present in a pulp, controlling the pH above 10.5 will ensure copper adsorption is minimal.

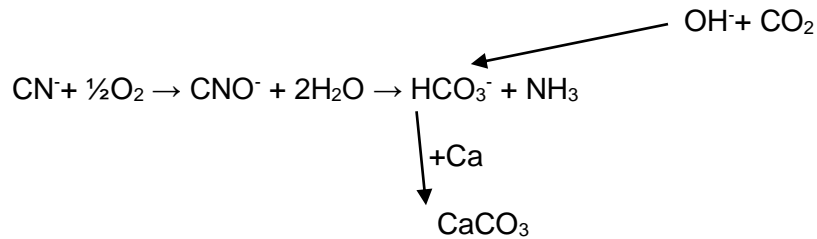
The base metal cyanides may be present in concentrations well above typical gold tenors, which will result in significant base metal loadings with gold. These poisons do not depress gold adsorption as significantly as the organic poisons do, however, they do need to be removed after each pass of carbon up a CIP or CIL circuit to reduce their effects on gold adsorption. Copper is an exception, with suitable conditions (pH lower than 10.5) very high copper loadings can be achieved, this being detrimental to gold adsorption, electrowinning and gold bar purity.

Base metal cyanides (excluding copper) are removed during acid washing and elution. If copper loading is a problem, a cold caustic cyanide pre elution wash will remove the copper. Acid washing will not remove copper as the copper cyanide species are converted to the inert and insoluble CuCN in acidic conditions.

7.4.2. Scale formation on activated carbon

The CIP process provides conditions that promote the formation of calcium scale, most commonly CaCO_3 (calcium carbonate).

Calcium is present due to addition of lime to control pH (typical lime concentrations are approximately 200 g/t). CO_2 , O_2 and CN^- are present to leach gold (using air or oxygen and cyanide). The following mechanisms are thought to occur:



High pH will enhance the above, stabilizing the anions in solution, allowing the above reactions to occur.

The activated carbon surface acts as a catalyst for scale formation on the surface of the carbon granules. The formation of scale is on the outer surface of activated carbon, the scale builds up blocking the meso and macro pores thus preventing gold from being adsorbed onto the carbon. Plant experience has shown that the effect of the scale on gold recovery by activated carbon starts to take effect when there is approximately 1,5 % calcium loaded on the carbon. The extent of depression of gold recovery by the scale is dependent on the CIP plant itself, in some plants 1,5 % calcium on carbon has an effect, while other plants survive with carbon loaded as high as 3 % calcium on carbon. Scale formation is not an equilibrium adsorption process and thus will not increase on every pass in a CIP adsorption circuit. It is a function of the "scaling index" conditions present in the solution phase of the pulp. Thus it is important to remove the scale prior to returning the carbon to the adsorption circuit. Scale is removed during acid washing. The CaCO_3 reacts with HCl to form $\text{CaCl}_2 + \text{CO}_2$ (or $\text{CaNO}_3 + \text{CO}_2$ with HNO_3).

Other scales like CaSO_4 , and magnesium scales, occur less frequently, but via similar mechanisms to the CaCO_3 scale formation. It is difficult to remove calcium sulphate from carbon using acid, it is best to prevent calcium sulphate poisoning. Other solid material (colloids) may be adsorbed onto the outer surface of carbon, or even simply occluded by the scale. Adsorbed colloids also block the meso and macro pores.

Examples are:

- Haematite (Fe_2O_3 = adsorbed colloid) gives dry carbon a reddish colour, most commonly found in CIP circuits treating roasted Calcine.
- Goethite ($\text{FeO}(\text{OH})$) (adsorbed colloid and occluded in scale) gives dry carbon a yellowish colour. This occurs most frequently when underground sludge is treated.
- Prussian blue (ferro – ferric cyanides – adsorbed colloid) gives dry carbon a dark blue colour. This occurs when a cyanide solution containing iron has its pH adjusted from 10 to acidic pH's, promoting the formation of Prussian blue. Other base metals behave in a similar way.
- Various forms of silica (e.g. shale, clay) (occluded) present as finely grinded ore. Silica is also slowly dissolved in adsorption circuits, turning silicates (Si-O complexes which load onto Carbon.

7.5. IONIC STRENGTH

The presence of cations in the alkali and alkali earth series (groups I and II of the periodic table, especially calcium) in the pulp is important as these ions form ion pairs with the gold cyanide ion, and enable the adsorption of gold by activated carbon.

7.6. pH AND CYANIDE CONCENTRATION

High pH values stabilize the $\text{Au}(\text{CN})_2^-$ ion in solution, thus lessening the chance of gold adsorption of the calcium gold cyanide ion pair. The lower the pH, the greater the chance of gold adsorption. However, at low pH's the formation of HCN is dangerous, thus the optimum operating pH for CIP/CIL plants is between 8 and 11.

Excess cyanide stabilizes the $\text{Ca}[\text{Au}(\text{CN})_2]_2$ on $\text{Au}(\text{CN})_2^-$ complexes, therefore promoting adsorption.

7.7. TEMPERATURE

The adsorption of the calcium gold cyanide ion pair by activated carbon is an exothermic occurrence, i.e. when gold is adsorbed, heat is generated. Thus gold adsorption by carbon is favourable when the temperatures are low; CIP plants generally perform better during cold winters rather than during hot summers. Conventionally, to remove (elute) gold from carbon, the temperature must be high.

7.8. GOLD TENOR AND CONTACT TIME

The amount of gold adsorbed by activated carbon increases with increasing gold tenor, this is dependent on the gold adsorption mechanism as discussed in previous sections. Since the adsorption of gold by carbon is to a certain degree rate controlled, the contact time will influence the amount of gold adsorbed. However, for cost purposes, contact time per CIP contactor is maintained between 10 to 60 minutes and typically 4 hours for CIL application.

7.9. ACTIVATED CARBON TYPE

The heart of any CIP or CIL plant is the activated carbon as it is the activated carbon itself that adsorbs the gold. Activated carbon itself will have an effect on gold recovery.

Activated carbon can be manufactured from a variety of raw materials, which define the structure (i.e. pore size distribution, hardness, etc) of activated carbon. The manufacturing process will also have an effect on the properties of activated carbon. Thus, there are a multitude of factors that will affect the properties of carbon. Since an activated carbon can be tailor made to suit certain applications, the factors most important for the specific application will determine the most suitable activated carbon. For gold recovery in CIP and CIL applications, these factors are:

- (i) Hardness – physical parameter.
- (ii) Kinetic activity – chemical parameter
- (iii) Equilibrium loading – chemical parameter
- (iv) Elutability – chemical parameter
- (v) Particle size characteristics – physical parameter
- (vi) Dense

Activated carbon made from coconut shells is the most common type carbon used in CIP or CIL plants.

7.9.1. Chemical parameters

The chemical parameters are chemical, they deal with the gold cyanide – activated carbon relationship. Two factors concern gold adsorption, one is the equilibrium loading and the other kinetic adsorption. High activity carbon is more expensive than low activity carbon, but the increase in kinetic gold activity can justify the price difference. Since plant conditions do influence gold recovery, some plants are over-designed to an extent where kinetic gold activity is not vital, thus cheaper low activity carbon can be used. However, all plants do have the ability to use high activity carbons, and since high activity carbons have high kinetic gold activity, less carbon will be required to recover the same amount of gold as with low activity carbons.

Kinetic adsorption is dependent on the activated carbon, while equilibrium loading is less so. Equilibrium loading is more dependent on plant conditions than on activated carbon.

If activated carbon can adsorb gold efficiently, then reversed conditions should allow for efficient elution. Thus an important factor of activated carbon is that it should not retain significant amounts of gold indefinitely, particularly under elution conditions.

7.9.2. Hardness

Activated carbon employed in CIL and CIP applications are subjected to harsh abrading conditions, particularly:

- Mixing in contactors.
- Abrading during transfer (pumping).
- Tumbling during regeneration.

A number of tests have been developed to determine the resistance of activated carbon to physical breakdown, examples are:

- Abrasion resistance; which determines the strength of activated carbon in wet conditions.
- Impact hardness, which determines the strength of activated carbon in dry conditions.

The conditions of CIP and CIL circuits are such that hardness and gold adsorbability are equally important, i.e. a good activated carbon for gold recovery is a compromise between hardness and gold adsorption properties. Coconut shell based activated carbons have been found to be the best suited carbon for this application at present, however variations in hardness have occurred, depending on the supplier or source of the carbon.

7.9.3. Particle size characteristics

The essence of the CIP or CIL process is that the gold is leached from the fine ore particles in the pulp and adsorbed onto the larger carbon particles. The carbon is screened out of the pulp in order for the gold to be recovered via elution. The carbon particles cannot be too large due to:

- Gold adsorption kinetics is related to particle size of the carbon.
- Availability of size of carbon material.

The size of the carbon is a compromise between ease of screening and carbon size.

Typical examples are given below:

INTERSTAGE SCREENS SIZE	ACTIVATED CARBON PARTICLE SIZE	ACTIVATED CARBON d50
1.11 mm to 1.0 mm	3.36 to 1.68 mm (6/12 mesh)	2.1 mm to 2.3 mm
1.0 mm to 0.65 mm	2,38 to 1,19 mm (8/16 mesh)	1.7 mm to 2.0 mm
1.0 mm to 0.65 mm	3.36 to 1,19 mm (6/16 mesh)	2.1 mm to 2.0 mm

Variations within the specified ranges do occur, thus specifications such as the d50 (particle size at which 50 % of the carbon will pass through) have been introduced. The typical d50s are those which give optimum results in activity and loss due to breakdown.

If slotted or wedge wire screens are used, then activated carbon with platelet (flat or flaky pieces) contents guaranteed should be used as high carbon losses could occur (with adsorbed gold) due to the flaky pieces slipping through the slots of the screens.

The fines content of fresh carbon should also be minimized as Carbon fines would pass through the screens in the CIL or CIP plant and report to tails.

8. DESORPTION (ELUTION)

The adsorption of gold by activated carbon is controlled by a chemical phenomenon, driven by a series of factors. Inversely changing key factors that favour adsorption will reverse the adsorption mechanism. As discussed in section 6, the most stable ion pair formed for gold is the calcium gold cyanide ion pair. This ion pair is present on the surface of activated carbon due to physical adsorption.

In order to elute gold off the carbon, the calcium gold cyanide ion pair must be changed into a form which the activated carbon will reject. i.e. the adsorption processes is reversed.

This occurs in two steps:

- Firstly, in the presence of excess sodium ions, (in 3 to 5 % NaOH for example) the calcium is ion exchanged for sodium forming the less stable $\text{Na} [\text{Au} (\text{CN})_2]$ ion pair. This is caused by the concentration effect of excess sodium ions.
- The less stable $\text{Na} [\text{Au} (\text{CN})_2]$ is not stable at elevated temperatures and so breaks down into its composite ions Na^+ and $\text{Au}(\text{CN})_2^-$ which carbon releases. This is the reason that heat is required during elution, the higher the temperature, the more effective the reaction.

Cyanide plays no role in the elution process. Gold can be effectively eluted off carbon using a hot dilute NaOH and/or water solution. However, if the gold present in a chemical form other than the calcium gold cyanide ion pair, the gold has to be converted into a form that it can be eluted. Cyanide would need to be added into the elution process if a carbon pre-treatment step that could break down the gold cyanide complex is utilized.

Hot acid washing can break down the calcium gold cyanide into polymeric AuCN or Au metal. Cold acid washing does not break down the gold cyanide complex. Other metals such as silver do not have a stable complex as gold and so could have their metal cyanide complexes break down in e.g. cold washing therefore cyanide should be present in low concentration if significant silver is present in the carbon circuit.

Since calcium promotes adsorption of gold, the presence of calcium in the elution cycle will depress elution, thus the water must contain as little calcium as possible. Sources of calcium are:

- (1) Water source, hard water contains more calcium than soft water, thus if hard water is the only available source, conversion of the water to soft water using ion exchange is suggested.
- (2) Additives; sodium hydroxide can contain up to 7 % calcium. Sodium Hydroxide with lowest levels of Calcium present should be used for elution.

Elevated levels of Calcium in water used for elutions would also increase levels of scale formations within the elution plant equipment, reducing the effectiveness of the elution process.

8.1. FACTORS INFLUENCING ELUTION

The most important factors are temperature and flowrate, since the kinetics (activated energy) and the thermodynamics (endothermic heat of reaction) of elution improve with increasing temperature. All elution plants operate at elevated temperatures, the modern trend is towards eluting at temperatures in excess of 100 °C, with the use of pressurized equipment.

High flowrates in the in the elution cycle (2 to 2.5 BV/hr) are important in order to mobilise or draw out the gold cyanide from within the carbon granules. Elution conditions are favourable for scale formation. Scale forms in areas of greatest seeding, such as heat source (heat exchange), nozzles in pipes etc. Scale formation will impede flowrate and reduce heat transfer, therefore negatively impacting elution. It is important to use as pure water and chemicals as possible.

Ionic strength is another factor that influences elution. The fact that elution increases with increasing anion concentrators but decreases with increasing cation concentrations means that the rate of elution passes through a maximum as the concentration of the eluting salt (e.g. NaOH) is increased i.e. too much elution salt will impede the elution process. The presence of cations that form strong ion pairs with gold cyanide, such as calcium can have a negative impact on the elution of gold if present in excess.

8.2. TYPES OF ELUTION

There are two approaches to the elution of gold from carbon, which have stood the test of time from both a commercial and technical perspective. The two processes are the AARL elution process and the Zadra elution process.

The difference between AARL and Zadra elution circuits is that the electrowinning is an integral part of Zadra circuits where electrowinning is decoupled in the AARL circuit.

8.2.1. AARL Elution

The AARL system is based on a batch elution over a 6 - 10 hour period. Initially the AARL elution cycle incorporated acid washing and elution in a single column. However, due to the necessity for special materials of construction, the general practice nowadays is to use separate acid wash and elution columns.

The loaded carbon from adsorption is transferred to a loaded carbon screen where the slurry is washed thereby separating the pulp from the carbon. The washed carbon gravitates into a loaded carbon bin that is typically 1 - 2 times larger than the elution column thus providing surge between adsorption and elution.

Carbon from the loaded carbon hopper is fed to the acid wash column. Acid washing can be performed prior to or post elution (after regeneration). The loaded carbon is washed with one bed volume (BV) of dilute hydrochloric acid followed by washing with one to two BV of water.

The acid washed carbon soaked with 1BV of a caustic - cyanide solution (typically 2 % NaOH and 3 % NaCN) at a temperature of 110°C for a period of 30 minutes. The initial plants used a soak solution of 2 % NaOH and 3 % NaCN. Recent plant experience has indicated that lower reagent concentrations yield acceptable elution results, in some cases the addition of NaCN has been eliminated.

After the soak the gold is eluted with 6 - 10 BV of high quality softened water (less than 300 g/t Na) at a temperature of 120°C and a flow rate of 2 BV per hour. Each batch elution can be completed on an 8 - 12 hour operating shift making use of an automatic control sequence and reagent pumps and valves. The eluted gold is in a high pH solution (eluate) which is pumped to the electrowinning circuit. The eluted carbon will be subjected to thermal regeneration prior to being returned to the adsorption circuit.

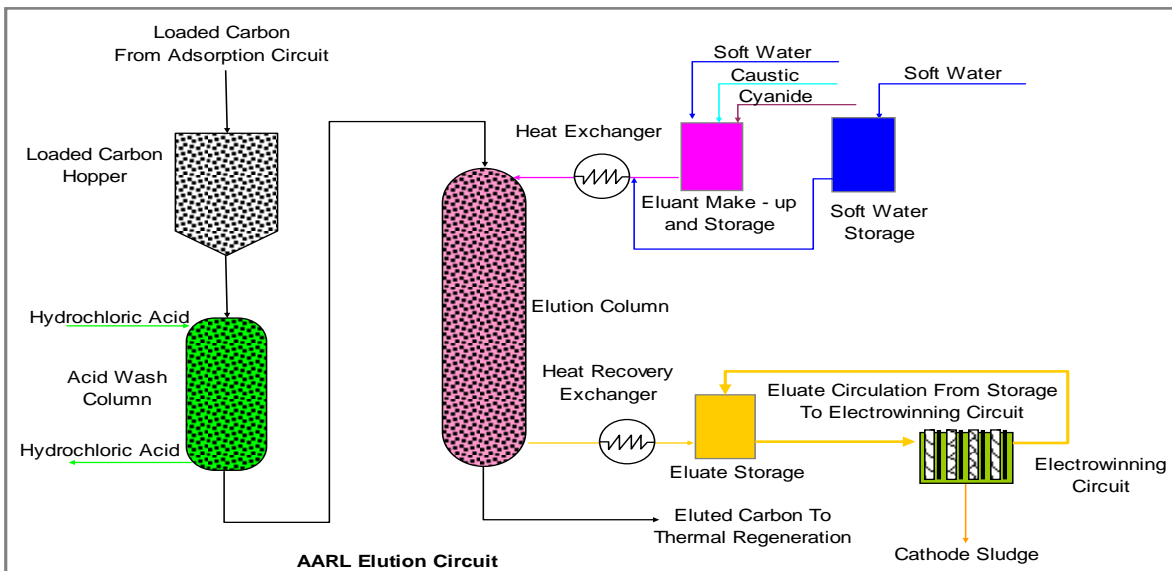
Flow through a column can either be upflow or downflow, upflow is generally preferred as it expands the carbon bed whereas the bed would be compacted when operating in a downflow mode. Solution distribution is effected via tabular wedge wire screens that can be removed, cleaned and replaced without having to open the column.

Carbon movement around the elution plant is effected by recessed impeller pumps, compressed air or pressurized water.

At elevated temperatures of 115 - 125°C the elution can be completed with approximately 4 - 6 BV's of eluate. At temperatures below 100°C the number of BV required can increase rapidly to 10 - 12 BV's.

The heating of eluate is achieved and controlled using heat exchangers. Early generation plants used low cost plate and frame heat exchangers, these were adequate for low volumetric flow rates. However, these are prone to scaling and choking and more recent larger plants have preferred shell and tube heat exchangers. Thermopacks are used to heat the thermic oil ring which feeds the shell and tube heat exchangers.

A typical AARL Elution Circuit is depicted below:

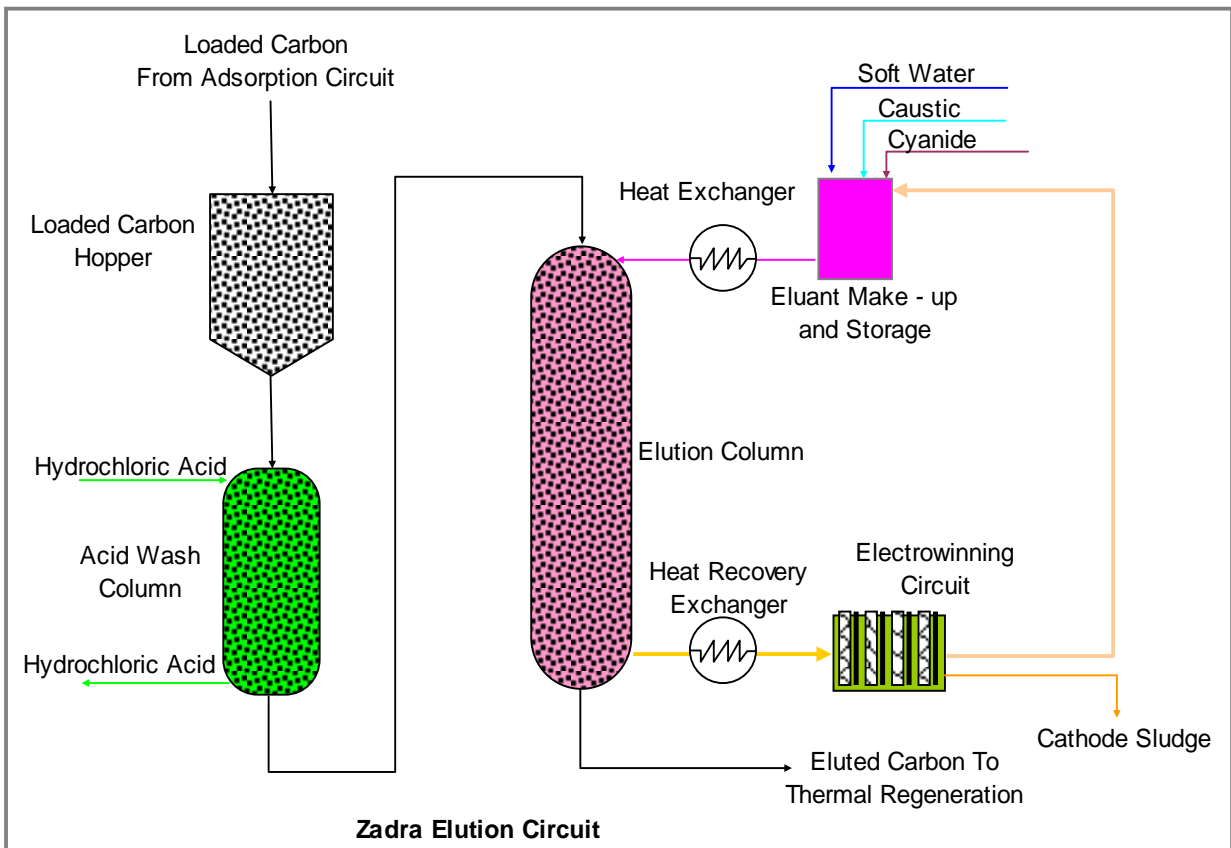


8.2.2. Zadra Elution

The Zadra elution process is different to the AARL elution process in that the elution and electrowinning operate simultaneously by continuous circulation of the eluate through the elution column and the electrowinning cells in series.

The eluate solution used in the Zadra elution process is typically 0.2 - 0.5 % NaCN and 1 - 2 % NaOH. All operating variables that apply to the AARL elution system apply to the Zadra system. In recent times, Zadra elution circuits do not add cyanide.

The caustic cyanide solution is pumped to the elution column at 2 to 3 BV/h, and is pre heated by the solution exiting the column. The temperature is then raised to approximately 130°C by means of a heat exchanger. After stripping the gold from the carbon the solution is partially cooled in the incoming heat exchanger and further cooled to below its ambient boiling point in a cooler heat exchanger. The solution flows to the electrowinning cells where the gold is stripped from the solution and returns to the elution column via the feed pumps. The duration of a Zadra based elution is typically 18 hours. A typical Zadra Elution circuit is depicted in below:



Typical Zadra Elution Circuit.

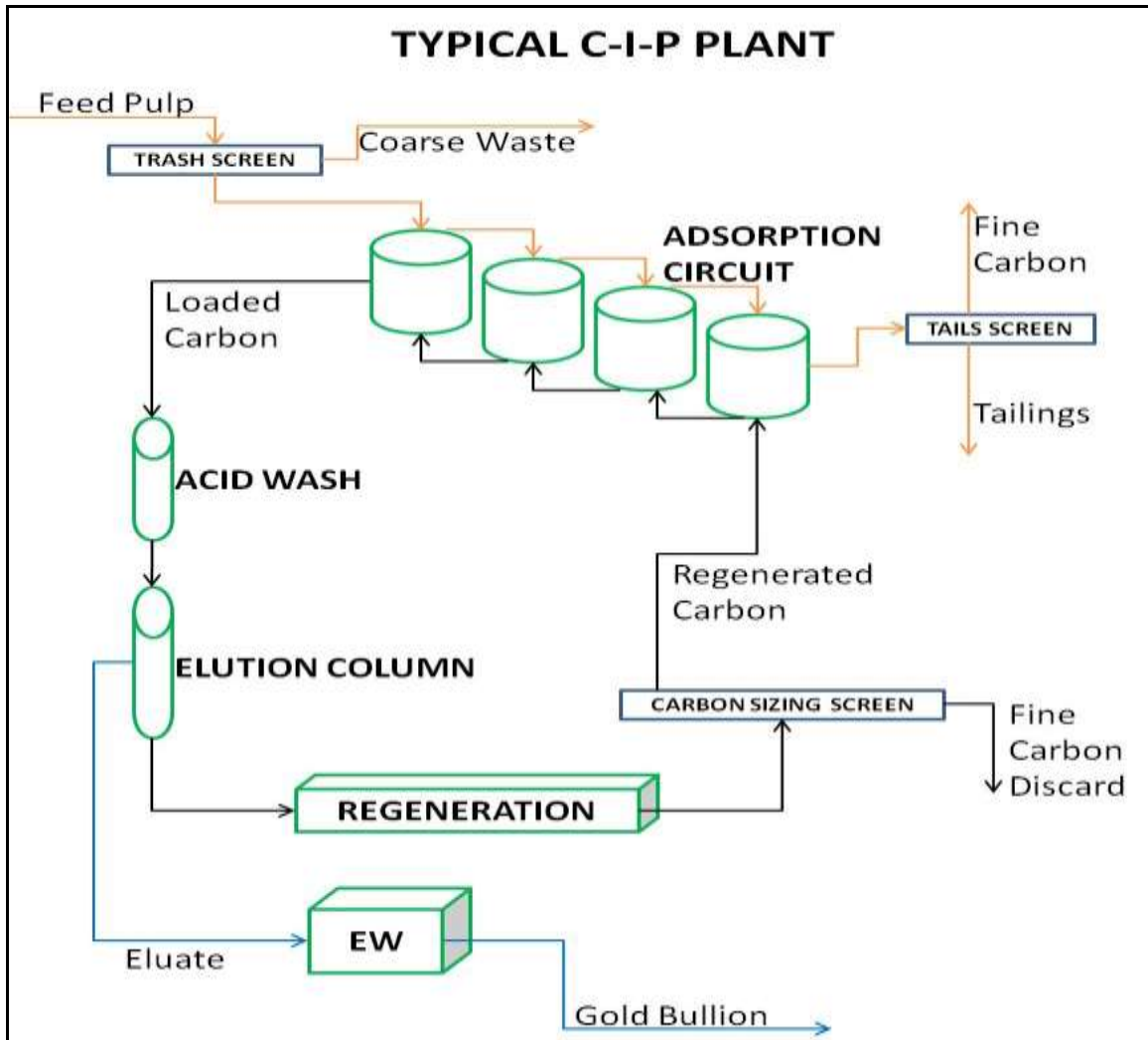
A question is often asked as to which is the best AARL or Zadra. The general consensus is that there is not a great deal to choose between the two and the choice often comes down to operator experience and performance. Zadra has tended to dominate in North America where it was initially developed while AARL dominates in the Southern Hemisphere.

Advantages of the AARL are its relative speed and the decoupling from electrowinning. The AARL requires less heat input. Advantages of a Zadra are perceived as a simpler flowsheet. Whichever system is used it remains important to elute effectively and obtain an eluted carbon value of approximately 50 g/t Au which is returned to the adsorption circuit

9. CARBON IN PULP / CARBON IN LEACH

Discussions on the CIP and CIL processes in previous sections dealt with the adsorption of gold in the adsorption section, however, the various factors discussed in section 8 complicate matters, particularly when the poisons are considered. The gold activity, (the affinity that activated carbon has for gold), is very important in the adsorption section, thus any drop in activity will result in a decrease in gold recovery. There are other unit processes required to remove the poisons and return the activity of the carbon to as close as possible to that of virgin carbon. Below is a scheme of a typical CIP or CIL Plant, the following major process steps are shown:

- Screening
- Adsorption circuit
- Acid washing
- Elution
- Regeneration and Electrowinning



9.1. SCREENING

Each type of screen has a specific function.

- Interstage screen:** These are the screens that operate within the tanks in the adsorption circuit. The purpose of these screens is to maintain the counter current transfer of activated carbon and pulp. The pulp flows down the circuit, while carbon is intermittently transferred up the circuit. The interstage screens prevent the carbon from flowing back down stream. Carbon has an average particle size of between 1.2 to 1.5 mm, the solids content of pulp would have a particle size of 0.1 mm or smaller. The interstage screen would have an aperture size of 0.6 mm to 0.8 mm to allow the pulp to flow through and keep the coarser carbon within the tank.

This is a unique screening process so suitable screens are specifically designed. Pulp is a difficult material to screen, particularly in situ. There is a pressure loss through the mesh of the screen (usually a wedge wire type) which is overcome using gravity to promote flow. This is the reason why tanks cascade at different levels in CIP/CIL adsorption circuits.

Pumping screens that lift and impart a horizontal intertank flow of pulp overcomes the required cascade tanks. Adsorption circuits using Pumping screens have the tanks arranged at the same elevation.

- **Pre screen or trash screen:** This screen is ahead of the adsorption circuit. All oversize and near size material, such as grit, wood fibre, explosive casings etc., are removed and so prevented from entering the adsorption circuit. Oversize material would blind the interstage screens as well as create numerous problems in the downstream the elution circuit. It is important that any process stream that would enter the adsorption circuit would pass through the trash screen. Linear screens and vibrating screens are commonly used.
- **Tails screen or safety screen:** This screening stage is post the adsorption circuit. This screen captures any oversize material that left the adsorption circuit. Near size carbon or an accidental bypass of carbon is captured by this screen. The value of the gold on the carbon as well as the carbon itself, necessitates this process step. Vibrating or linear screens are most commonly used, linear screens are also used.
- **Loaded carbon harvesting screen:** The loaded carbon is separated on this screen. This screen provides two functions, separating the carbon from the pulp which returns to the adsorption circuit, and washing the carbon to remove entrained fine ore. Fine ore particles would have negative effects on the downstream elution processes. Vibrating screens are the most suitable type of screen for this function.
- **Carbon sizing screen:** This screen removes the undersize carbon particles generated during acid wash, elution and regeneration steps. The undersized carbon would pass through the interstage screens and report to tails usually taking some gold, if not removed during this process. Vibrating screens are the most suitable screens.

The apertures for the various screens should be matched to ensure efficient control of carbon:

	Option 1	Option 2
Carbon size (mesh ASM)	6 x 12 or 8 x 16	6 x 12 or 8 x 16
Trash screen (microns)	600	700
Tails screen (microns)	600	700
Interstage screens (microns)	650 to 700	800
Loaded carbon screen (microns)	600	700
Carbon sizing screen (microns)	1200 to 1500	1200 to 1500

The interstage screen mesh wears during use and is replaced when the apertures are approximately 1200 microns.

9.2. ADSORPTION / ELUTION / ACIDWASHING / REGENERATION

The two process steps (thermal regeneration and acid washing) are present only to remove poisons. As these two steps do not directly handle gold, they are generally given lower priority in terms of effort in plant control. They are the most misunderstood process steps and often are the cause of loss of gold recovery). A slight loss of activity can result in a reduction in solution gold extraction efficiency, e.g. from 60 % to 50 % . This reduction in extraction efficiency will result in an increase in solution residue tenor which means recoverable gold is lost to residue. As a result, the measurement of the performance of the CIP/CIL circuit can be determined by how low the solution gold loss is.

9.3. ACID WASHING

Acid washing is used to remove the scale by converting CaCO_3 to CaCl_2 (when using HCl), which is soluble in water. This is a rapid reaction and does not require heat. This step also removes the base metals such as Ni, Fe and Zn, but, since the cyanide complexes are either being destroyed to form chloride salts (Ni, Zn) or rearranged (Fe), heat is required to effectively remove the base metals, however cold acid washing will remove a significant amount of base metals. Acid washing is generally undertaken prior to elution, however it may be undertaken after regeneration

HNO_3 and HCl acids are generally used. The acids are used in dilute form, usually below 10 % . Since the removal of scale is a reaction, it is important that all the scale is removed. Sufficient acid is required to complete the reaction, therefore there should always be residual acid left after acid washing is complete.

9.4. THERMAL REGENERATION

Thermal Regeneration removes the adsorbed organic species. The organic species are removed by heating the carbon to elevated temperatures in the presence of steam without damaging and weakening the carbon granules. During the regeneration process the following occurs:

- Drying:

Activated carbon is fed into the kiln containing $\pm 50\%$ w/w entrained water. Water is heated and boils off the carbon and creates the saturated steam atmosphere within in the kiln. The water within the carbon pore structure converts to steam during the drying phase. This entrained steam escapes from the pores and cleans the carbon, removing certain foulants. Some inorganic species may deposit on the inside of the retort tube.

- Vaporization

During heating to the regeneration temperature, the organic species are removed by vaporization. The organics are heated to temperatures high enough to break the Van der Waals forces and the organics are boiled off. Some organic species decompose into more volatile fragments, while other organic species pyrolyse, leaving a carbonaceous residue in the carbon.

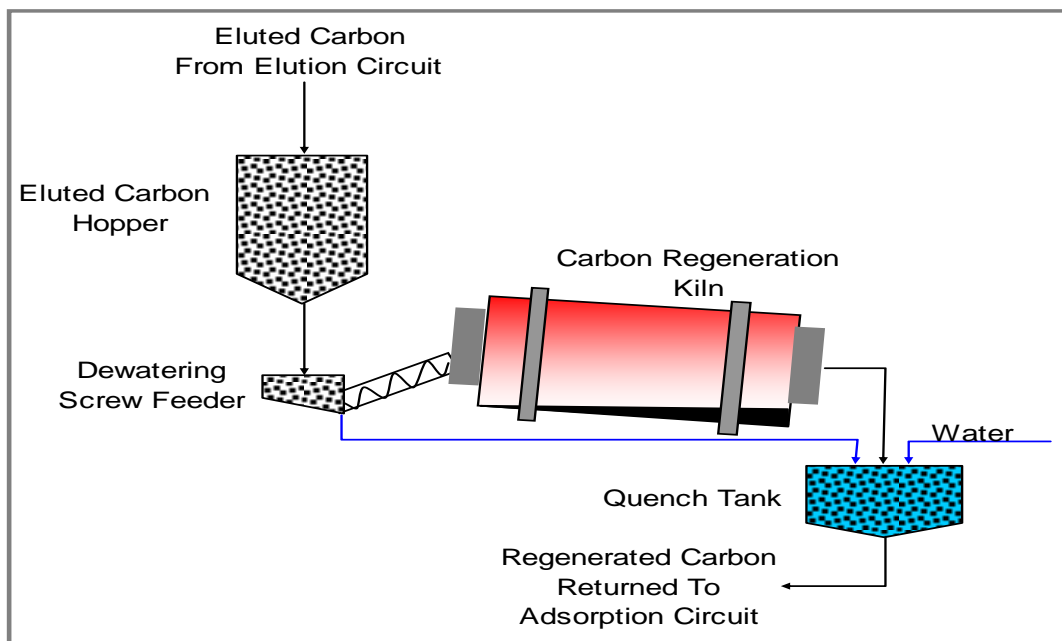
- Pyrolysis and selective oxidation. The carbonaceous residue within the carbon granules is selectively oxidised by the water gas reaction. This is called reactivation of the carbon and carried out above 800 °C.

The extent of fouling of carbon by organics in the CIP/CIL plants is low compared to applications in which carbon is used to remove organic species. The extent of pyrolysis is low as well, therefore it is not a requirement to reactivate carbon used in CIP/CIL plants.

The generally accepted conditions to optimally thermally regenerate carbon activated carbon in the gold industry are as follows:

- 650 to 750 °C for 10 to 15 minutes.

A typical regeneration kiln arrangement is depicted below



10. THE IMPORTANCE OF CIRCUIT AND ACTIVITY PROFILES

The gold adsorption process is defined and affected by external factors and the measurement and evaluation of this data aids in identifying and solving adsorption inefficiencies.

If something changes in the adsorption process, the impact is generally negative, which reduces the gold solution value, i.e. the gold in solution tails increases.

In the counter current CIP and CIL or Carousel plants, the movement rates between carbon and pulp are different. The pulp moves continuously down the circuit whereas the carbon is moved up intermittently. The pulp would spend between 10 minutes (in a high intensity Pumpcell tank) to 4 hours (in a CIL tank), thus the activated carbon in each tank has a limited time to adsorb as much gold as possible, therefore adsorption kinetics plays a significant role.

The carbon stage inventory or part thereof is moved once a day from tank to tank. This may be via complete batches as in carousel circuits to continuous transfer in some CIP/CIL circuits. A constant feed in terms of pulp flowrate and gold concentration (which is normal for gold plants) will result in the activated carbon reaching an equilibrium between the gold on carbon and gold in solution in the tank.

Since the tanks in the adsorption circuit follow each other, the independent equilibrium and kinetic performances for each tank follow suit, and can be related to each via other profiles.

These profiles are:

- Gold-in-solution profile – This is the measurement of gold in solution phase in each tank. Comparing the values to each other should result in an extraction percentage averaging 60 % per stage throughout the circuit. This is a measurement of kinetics extraction.
- Gold-on-carbon profile – This is the measurement of gold-on-carbon in each tank. Comparing the values to each other should result in a reduction of 50 % per stage down the circuit. This is a measurement of pseudo equilibrium gold loading.

Examples of typical profiles for a CIP plant are as follows:

	Gold in Solution Profile		Gold on Carbon Profile (g/t)
	Extraction (%)	Value (mg/l)	
Feed		5.000	-
Stage 1	60	2.000	5 000
Stage 2	60	0.800	2 025
Stage 3	60	0.320	835
Stage 4	60	0.128	353
Stage 5	60	0.051	169
Stage 6	60	0.020	93
Stage 7	60	0.008	62
Eluted Carbon	-	-	50

If, something goes wrong in the process, and the stage extraction efficiency drops from 60 % to 50 % , the values change:

	Gold in Solution Profile		Gold on Carbon Profile (g/t)
	Extraction (%)	Value (mg/l)	
Feed		5.000	-
Stage 1	50	2.500	5 000
Stage 2	50	1.250	2 506
Stage 3	50	0.625	1 258
Stage 4	50	0.313	635
Stage 5	50	0.156	323
Stage 6	50	0.078	167
Stage 7	50	0.039	89
Eluted Carbon	-	-	50

A seemingly small decrease in the extraction efficiency has resulted in a significant increases (5 fold) of the solution residue. The amount of gold loaded onto the carbon has not changed as significantly.

The profiles above show that, even though the kinetic and equilibrium performance of carbon are related, they can also operate independently. Activated carbon is able to adsorb and load gold to acceptable levels even if the carbon is negatively impacted to the extent that its kinetic performance is poor.

By measuring the solution and carbon profiles on a regular basis the analysis of these profiles aids in identifying problem areas. Since the circuits are continuously operating, the measurement of the profiles within the circuit should be planned and executed with as fast as possible turn around of accurate results. Since the profiles provide valuable plant management information, it is suggested that the profiles are measured routinely – daily for solution profile, less frequently for the carbon profile.

The factors that affect the profiles are as follows:

10.1. ACTIVATED CARBON TYPE

Adsorption circuits are generally aggressive on activated carbon. It is typical for a plant to consume an inventory of carbon per year. It is important that the carbon purchased meets the specification required, and that the specification suit the application. Basically, carbon must be:

- Hard enough.
- Active enough.
- Have the right particle size (minimal fines and platelets).

Poor quality carbon impacts both profiles.

10.2. ACTIVATED CARBON CONDITIONS

As previously discussed, activated carbon adsorbs any neutral species. These species could be organic or inorganic and compete for adsorption sites and block pores preventing adsorption of gold. The poisoning of activated carbon impacts on the kinetic adsorption characteristics of carbon and manifests in negatively impacting the solution profile. Poisoned carbon will result in higher solution gold losses in residue. Poisoned carbon will still reach equilibrium gold loadings (albeit slowly) due to the high affinity carbon has for gold.

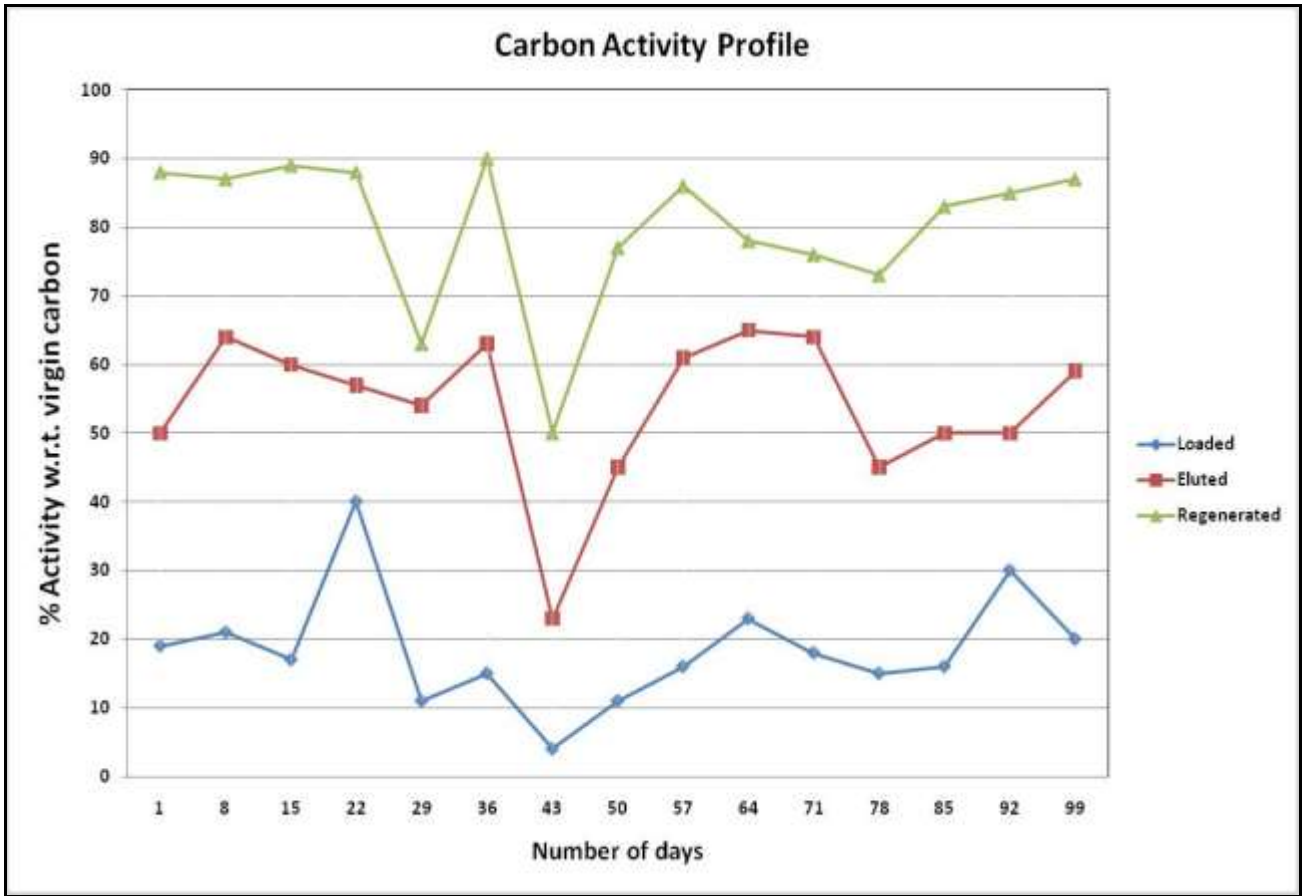
A third profile that is an important monitoring tool is the **carbon activity profile**, the measurement of the kinetic activity of carbon before and after each treatment step in the elution plant. The effect of the presence of poisons on loaded carbon, eluted carbon, acid washed carbon and regenerated carbon is determined. Comparison of the activity of carbon after each step will indicate the importance of each step. Comparing the variability over time will allow each step to be managed in terms of their efficiency.

There are only two steps that remove poisons:

- Acid washing (inorganic poisons removed).
- Regeneration (organic poisons removed).

If a major problem occurs in either of these two steps e.g. total kiln malfunction, then the corrections necessary are obvious. However, less obvious and generally unmonitored smaller problems can occur, resulting in a decrease in the gold recovery efficiency of the activated carbon. CIP and CIL plants are overdesigned to the extent that a small drop in the gold recovery efficiency of activated carbon will not adversely affect the gold recovery in the adsorption circuit. However, the carbon will reach a state (usually after a few weeks) that it has lost activity to an extent that it is not able to adsorb the gold, resulting in a dramatic increase of solution gold loss from the adsorption circuit.

Since activated carbon takes from seven days to weeks to pass through the adsorption circuit and elution plant small inefficiencies in the two poison removal stages are best defined by testing the entire inventory of carbon by making up weekly composite samples of all the carbon instead of taking grab samples. Composites are generally made up weekly then evaluated for kinetic gold adsorption rate "activity" using standard methods. An example of activity profiles are given in the graph below.



As can be seen the gold activity of the carbon increases as the carbon passes each successive poison removal stage. The poison removal stages differ from plant to plant in terms of scheduling, however what is common for all well operated plants is that the carbon activity being returned to the adsorption circuit is within 80 to 90 % of virgin (fresh) carbon activity. Activity values below 80 % means that at least one poison removal stage is not working at optimum. Activity above 90 % exposes the carbon to risks of burning in the regeneration step, resulting in a weaker carbon which breaks down in the adsorption circuit. The monitoring of the "carbon handling stages" (poison removal operations) is best undertaken by a well equipped laboratory.

10.3. PLANT VARIABILITY AND BALANCING

There are a number of factors that affect the extent of adsorption of gold on carbon. A balanced plant has no variability and would therefore operate optimally (producing the highest loading with the lowest solution gold loss). Important factors that should vary as little as possible are:

- **Throughput.** A change in throughput will change the amount of gold content in the feed to the circuit. This will cause the gold-on-carbon profile to change most significantly in the first few tanks. For a CIL, an increase in throughput may compromise the leaching efficiency as residence time is reduced.
- **Head grade in feed.** This will affect both gold-on-carbon and gold-in-solution profiles most significantly if there is a sudden drop in head grade value. CIP/CIL circuits are robust when well operated and can easily cope with an increase in grade. The gold-on-carbon increases and the extraction of gold by carbon is maintained because carbon has the capacity to load. The problem with head grade variation occurs when the head grade falls sharply by a large percentage e.g. 20 % or more. The gold and the loaded carbon in Tank 1 is at a pseudo equilibrium with the original higher grade, a drop in gold grade will result in carbon in Tank 1 slowing adsorption rate or even reversing adsorption to reequilibrate. The gold in solution grade is compromised with the result of an increase in solution gold residue. It is important to plan to move highly loaded carbon out of the circuit if the gold grade in the ore is planned to reduce in value.
- **Carbon movement rate.** A well operated adsorption circuit has a balance between the three profiles and carbon movement rate, whether cascade or carousel. A change in the movement rate can imbalance the profiles and compromise residue. This is particularly noteworthy in cascade circuits when the rate of loaded carbon movement exiting the circuit is at not the same rate. The danger of this is the carbon in Tank 1 can be depleted, the carbon concentration reduced to a point when gold extraction is significantly reduced to the extent that the carbon in Tank 2 behaves as if it is in Tank 1. The adsorption circuit has effectively lost an operating tank. It is normal practice to have a higher carbon concentration in Tank 1 in cascade circuits.
- **Eluted carbon value.** It is important to ensure the gold on eluted carbon is as low as possible to ensure that the gold-on-carbon and gold-in-solution profiles are not compromised in the last two or three tanks, If the gold value on eluted carbon is too high then the carbon will either not extract or even desorb gold in the last tank. Eluted carbon values should be 50 g/t or lower.

A balanced plant has an optimal equilibrium profile. Unbalancing the profile manifests in an increase in gold in solution in the residue. Besides the factors discussed above, one problem that affects the balancing of the plants is the **performance of the interstage screens**. The purpose of these screens is to allow pulp to pass through the circuit but retain the coarser carbon. If the screen fails in one tank, then carbon will flow in to the next tank resulting in non-uniform distribution of carbon within the circuit.

Another problem is the **presence of near size material**. Near size material – usually near size grit and trash should be removed by the pre screen or trash screen. The presence of an accumulation of near size material results in::

- Dilutes the carbon in elution plant.
- Blinds interstage screens.

Both of the above would result in the unbalancing of the circuit by slowing down carbon movement rate or back mixing of carbon in the tanks because Interstage screens overflow etc.

Near size material cannot be screened off because of its near size! It can only be removed by:

- Elutriating or backwashing the carbon in a column. Light material such as wood fibre or plastic are removed.
- Spiral classification to remove heavier grit material.

11. SAMPLING, SAMPLE PREPARATION AND SAMPLE CONTAMINATION

The collection and preparation of samples in a carbon circuit (CIP/CIL) must take into account all that has been discussed in this article to ensure accurate information is obtained.

In all gold circuits it is very important to know when, where and how to sample to ensure that the plant is performing optimally.

Samples should be taken from the feed, discharge and all the stages on a regular basis. Regarding the interstage samples it is important to take the samples from a representative position in the tanks. Samples should be taken by starting at the discharge (lowest solution gold concentration) and ending at the feed. (Highest solution gold concentration). Once the sample, containing slurry and carbon has been taken, there are two very important points that should be noted.

- Firstly, the carbon should be separated from the slurry immediately to prevent further adsorption of the gold onto the carbon. If the sample is not separated immediately the carbon has additional adsorption time to absorb gold, this can be anything from an hour to half a day.
- A second point to consider is to filter the slurry sample as soon as possible to separate the solids from the solution phase. This is to prevent further leaching of the solids which will also effect the solution gold concentration. This will have the biggest effect on the last couple of stages in the CIP/CIL operation where the solution gold concentration are already significantly low (below 0.01ppm) and any further leaching can influence the results to give inaccurate tailings values. The gold on carbon profile is not effected by this.

The same procedures should be followed when sampling a carousel circuit than when sampling a continuous, cascading CIP/CIL operation. However, in a carousel circuit the feed and discharge points are continuously being moved to simulate a counter current operation. Hence the stages are continuously changing, meaning that tank 1 will not necessarily be the head tank and so forth. At startup tank 1 will be head tank until the carbon in tank 1 has reached the desired gold concentration. Then tank 1 will be taken offline and tank 2 will become the new head tank. It is very important to keep record of this process to be able to analyze the analytical results correctly.

12. CARBON-IN-LEACH (CIL) CARBON-IN-PULP (CIP), CAROUSEL CIP AND PROCESS SELECTION

There are predominantly three methods employed in industry to adsorb leached gold from a pulp stream onto activated carbon. The methods are Carbon-in-Leach (CIL), Carbon-in-Pulp (CIP) and Pumpcell technology. CIL and CIP are typically counter current operations while the Pumpcell technology makes use of the carousel mode of operation. However, a few carousel CIL operations have been constructed in recent years.

12.1. CARBON-IN-PULP (CIP)

In a CIP operation the majority of the leachable gold has been leached prior to the first carbon adsorption stage. The gold adsorption is carried out in specifically designed tanks that are situated after the leaching tanks. The adsorption tanks are typically a quarter to a tenth of the volume of the leach tanks.

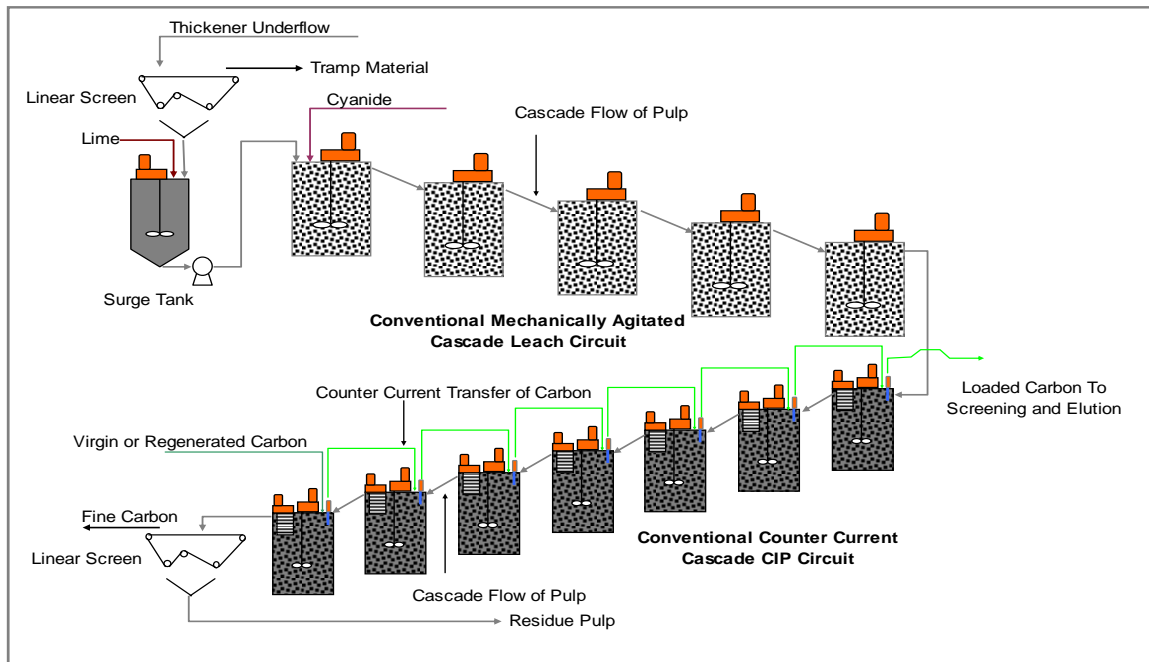
The CIP mode of operation occurs in a number of adsorption tanks placed in series. Pulp flows continuously from the first tank to the last, while carbon is pumped counter current from the last to the first tank. Carbon movement is carried out using interstage pumps. The carbon inventory is progressively pumped up the adsorption train, the inventory in the individual tanks will have to be monitored to ensure that the inventory is balanced evenly throughout the circuit.

As the pulp flows down the CIP adsorption train the gold value of the solution decreases to give a barren solution value in the final tank. On carbon adsorption plants a solution tenor exiting the final adsorption tank is typically lower than 0.010 mg/l gold in solution. The gold on carbon loading will increase as the carbon is pumped up the adsorption tank. The carbon exiting the first train in the adsorption train is called loaded carbon. The loaded carbon is then transported to the elution section.

On a CIP operation one typically achieves an upgrade ratio of between 1000 to 1200. The upgrade ratio is the ratio of the feed gold tenor, gold in solution, to the loaded carbon grade, g/t gold adsorbed onto carbon. A CIP operation will typically be designed to have a stage residence time of one (1) hour. In order to adsorb the gold in solution, CIP circuits operate at a carbon concentration of between 20 - 25 g/l of carbon.

A phenomenon associated with both CIP and CIL operations is back mixing. Back mixing occurs when carbon is pumped via the interstage pumps up the adsorption train. Remembering the fact that pulp flows downstream while a combination of carbon and pulp is pumped upstream results in an intermittent dilution of gold in solution. The transfer of carbon also mixes carbon having different loadings.

A typical leach and CIP adsorption circuit is depicted below:



12.2. CARBON-IN LEACH

The CIL mode of operation is when the leach and adsorption circuits are combined into a single process. A CIL circuit is advantageous when the presence of carbon enhances the leach efficiency by competing with other gold adsorbing (preg robbers) constituents in the ore.

A CIL operation operates on much the same way as a CIP operation. Pulp flows down the adsorption train while the interstage screening of carbon allows the gold depleted pulp to pass through while retaining the carbon granules in the tank. The carbon is pumped intermittently up the CIL train using interstage pumps.

The main difference between CIP and CIL lies in the extent to which gold is leached prior to carbon adsorption. In the CIP process most of the leachable gold has been leached prior to the first adsorption stage. In the CIL operation, carbon is added to the leaching tanks, therefore the leaching reaction and adsorption occur simultaneously.

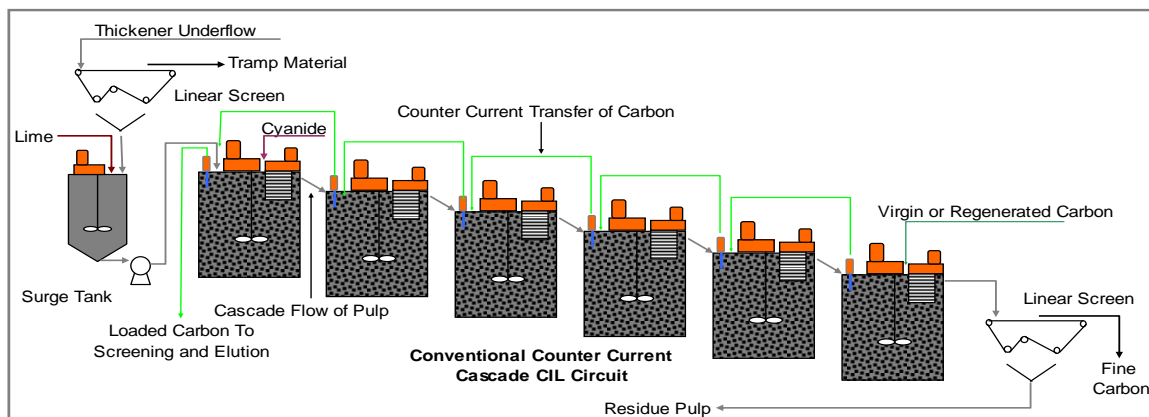
The kinetics of gold adsorption on carbon is slower in a CIL than in a CIP. This is due to the fact that leaching is incomplete when pulp encounters carbon in the CIL adsorption tanks and consequently the concentration of gold in solution is lower. To compensate for a decrease in the kinetic driving force more carbon is required to match the metallurgical performance achieved on a CIP.

The carbon concentration on a CIL is typically 5 to 15 g/l. Therefore more pulp is transferred upstream in a CIL circuit thus backmixing during counter current transfer of carbon is increased relative to a CIP operation.

The net result of the increase in total carbon inventory coupled with the reduction in the concentration of gold in solution as a result of an increase in backmixing in a CIL circuit operating at a lower theoretical upgrade ratio relative to a comparative CIP circuit. The theoretical upgrade ratio for a CIL circuit is 800 - 1000.

The only tangible advantage a CIL has over a CIP and Pumpcell technology is in negating the effects of preg robbing constituents present in the ore body.

A typical CIL adsorption circuit is depicted below.



12.3. PUMPCELL CIP

Pumpcell technology was developed with a view to introducing an alternative approach to the design of conventional cascade CIP adsorption circuits.

The carousel mode of operation is that the pulp feed and tailings discharge positions are rotated on such a manner that a counter current movement of carbon is achieved without the need to physically move carbon from one tank to another. The carousel mode of operation has been shown to result in a significant improvement in metallurgical efficiencies as backmixing has been eliminated and carbon management is improved as the carbon is managed in discrete batches.

The Pumpcell is designed to operate at a low residence time of 15 minutes per stage. Consequently the Pumpcell is significantly smaller than both the CIL or CIP options. The ability to reduce the residence time per stage is as a result of operating the plant at a higher carbon concentration of 50g/l.

As carbon is managed on a batch basis the intermittent interstage pumping of carbon is not required.

The lead Pumpcell receives fresh pulp from the feed launder located above the Pumpcell top platform. The feed launder valve arrangement directs the flow of pulp into the desired Pumpcell.

As all the Pumpcells are at the same horizontal elevation the cascade flow of pulp between the individual Pumpcells is not possible. The movement of pulp between the Pumpcells is effected by the Pumpcell mechanism. Pulp is drawn through the wedge wire screen by virtue of the up-pumping impeller developing a head in the open volute, which is connected to the internal launder. The head and horizontal velocity created by the pumping action is sufficient to overcome launder losses and allows for the velocity flow of pulp to the next Pumpcell.

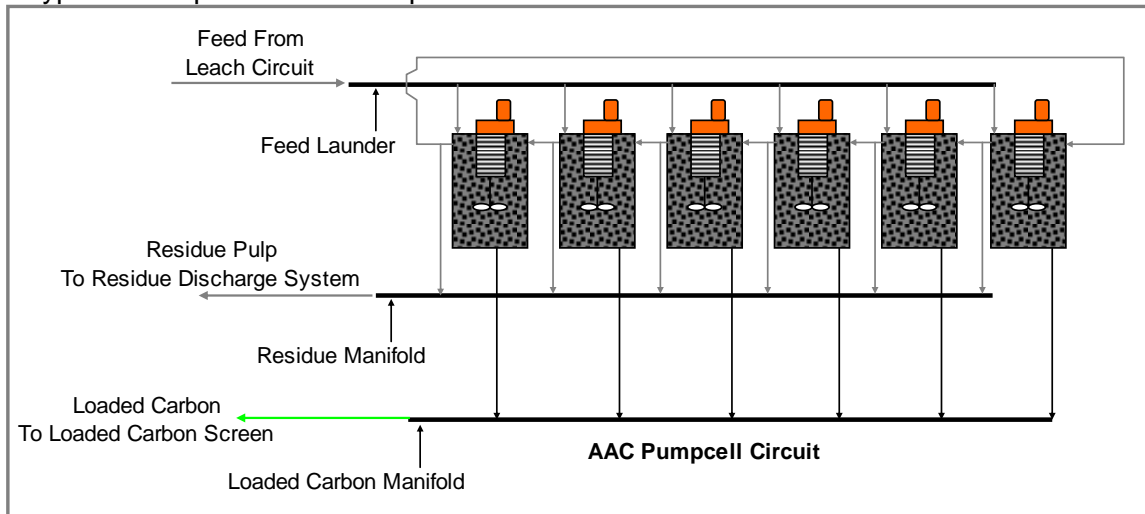
When the gold on carbon loading in the lead Pumpcell has reached the predetermined value the lead Pumpcell is isolated and the feed material is directed to the second Pumpcell in the carousel sequence.

The second Pumpcell effectively becomes the new lead Pumpcell. The entire contents of the lead Pumpcell is drained and pumped via a recessed impeller pump to the loaded carbon screen, on which the loaded carbon is harvested and the pulp is returned to the feed tank of the Pumpcell.

When the contents of the original lead Pumpcell has been drained the Pumpcell is brought back on line as the new tail Pumpcell, and a predetermined amount of regenerated or virgin carbon is ordered. This procedure of rotating the lead and tail Pumpcells form the basis of rotating the carousel sequence.

Being a carousel model of operation, the Carbon in the Pumpcell plant is contained in batches. There is no batch mixing of carbon which occurs in counter current transfer of carbon in CIP and CIL circuits. As a result of this the loading of gold on carbon in the circuit changes with time and the time to harvest the loaded carbon can be chosen on the basis of value. Higher upgrades ratios above those in CIP can be achieved, usually 1500 to 2500, sometimes higher for Pumpcell plants.

A typical Pumpcell circuit is depicted below.



12.4. CHOICE OF ADSORPTION CIRCUIT

As described in the previous sections, there are a number of choices for a suitable adsorption circuit to recover gold from in-pulp streams. The choice of circuit should be defined as what is most suitable for the process stream.

As an example of a typical gold plant, the following two tables demonstrate the impact of choice of circuit. The material is suitable to be treated using CIL, CIP and Carousel Pumpcell circuits. The choice of circuit defines the gold loading on loaded carbon due to upgrade ratio expectations. This is on the basis that gold loss in solution residues is not compromised. The higher the gold loading, the lower the elution requirements. Considering that rate of elution is not gold loading limiting, the size of the elution plant is not defined by gold loading on carbon. The cost of elution is defined per ton of carbon, energy being the most significant cost contribution. As can be seen in the second table, significant cost can be saved by choosing the circuit that utilizes the lowest elution requirements.

Not all process streams can be evaluated on the basis described:

- Process streams containing preg-robbing components (components that adsorb gold in competition to activated carbon) would use CIL.
- High grade concentrate circuits downstream from pre-treatment steps such as BIOX, roasting, POX and fine re-milling would have circuits defined to maximizing gold recovery rather than most favorable operating costs.

CIL, CIP, PUMPCELL COMPARISON

PARAMETER	Unit	CIL	Leach / CIP	Leach / Pumpcell
Feed Rate	t/month	250,000	250,000	250,000
Percentage Solids	%	45	45	45
Pulp Density	t/m ³	1.41	1.41	1.41
Flow Rate	m ³ /h	549	549	549
Head Grade (Au)	g/t	1.52	1.52	1.52
Theoretical Gold Production	kg/month	323	323	323
Theoretical Upgrade Ratio	No.	900	1,100	1,490
Loaded Carbon Grade	g/t	961	1,174	1,591
Loaded Carbon Eluted	t/month	355	287	210
Elution Plant Required	ton	12	10	7
Leach Residence Time	hours	18	18	18
Volume of Leach Tanks	m ³	1,650	1,650	1,650
Volume of Adsorption Tanks	m ³	0	550	150
Carbon Concentration	g/l	10	20	50
Carbon Inventory	ton	99	66	45
Back Mixing	m ³ /h	148	60	0
Back Mixing	%	27	11	0
Adsorption Residence Time per Contactor	minutes	0	60	16
Regeneration Kiln Size	kg/h	600	500	350
Number of Electrowinning Cells Required	No.	5	5	4

OPERATING COST COMPARISON

	Unit	CIL	Leach / CIP	Leach / Pumpcell
LEACH - ADSORPTION				
Feed Rate	t/month	250,000	250,000	250,000
Operating Cost (Leach - Adsorption)	ZAR/ton	1.500	1.500	1.500
Operating Cost (Leach - Adsorption)	ZAR/month	375,000	375,000	375,000
ELUTION - REGENERATION				
Carbon Treatment Rate	t/month	355	287	210
Operating Cost (Elution - Regeneration)	ZAR/ton (carbon)	4,500	4,500	4,500
Operating Cost (Elution - Regeneration)	ZAR/month	1,595,682	1,292,657	943,331
OPERATING COST	ZAR/month	1,970,682	1,667,657	1,318,331
OPERATING COST	ZAR/ton	7.88	6.67	5.27