

Meeting the challenge of Penjom Gold Mine's geology in the recovery of fine gold in carbonaceous ores

SIEARRA CELASTRA SARINA RAMLI^{1*} & RAMLI MOHD OSMAN²

¹University of Western Australia, Faculty of Engineering,
Computing and Mathematics, 35 Stirling Highway, Crawley, WA 6009.

²Minerals and Geoscience Department Malaysia, Mineral Research Centre,
Jalan Sultan Azlan Shah, 31400 Ipoh.

*Corresponding author: celastra.ramli@gmail.com

Abstract: Ore bodies that were previously deemed unfeasible to mine have now become economically feasible due to the increase of gold price in recent years. In addition to the increase in gold price, some processes that have been under development have now been proven viable. Also, the geology of a mine would influence the recovery strategy of the gold from the ores. Evidence of this is seen at Penjom Gold Mine (PGM) in Malaysia, where carbonaceous gold ores are mined and processed. PGM produces one of the world's worst preg-robbing gold ores, yielding very low recoveries from traditional carbon-in-leach methods. Preg-robbing is preferential absorption of gold-cyanide complex ions $[\text{Au}(\text{CN})_2^-]$ by organic carbon in the carbonaceous gold ores. The gold processing facilities in PGM are designed to address the challenges of fine gold recovery from carbonaceous and sulphide ores. Since employing the resin-in-leach process in mid-1999, gold recovery rates consistently run close to 90% which is a remarkable 30% improvement over recovery rates using activated carbon. The resin-in-leach process is not as common and appears as a result of thorough development work conducted since late 1940s. The objective of this paper is to analyse how preg-robbing carbonaceous gold ores can be processed economically. This objective will be achieved through literature research and using the most recent practical work findings from PGM. Optimization of process parameters in order to achieve acceptable gold recovery under low operating costs will be emphasized. The most important finding from this paper is the success of the resin-in-leach process in recovering gold from carbonaceous gold ores and the most up-to-date process parameters of cyanide concentration, temperature, and pH used in the hydrometallurgical circuit.

Keywords: Penjom Gold Mine, very fine gold, preg-robbing, resin-in-leach, process parameters

INTRODUCTION

The geology of Penjom Gold Mine (PGM) in Malaysia is such that gold is mineralised in quartz veins together with sulphide minerals and organic carbon in the ores. Even though the sulphide contents in PGM are low, i.e. less than 3 volume % (Lim *et al.*, 2001), the issue of recovering gold interlocked in the sulphide minerals is also addressed in this paper.

The most challenging gold recovery strategy faced by PGM is that it produces one of the world's worst preg-robbing gold ores, yielding very low recoveries from traditional carbon-in-leach (CIL) methods (Lewis, 1999). A resin-in-leach (RIL) gold recovery process was implemented in place of the CIL process. Since employing the RIL process in mid-1999, gold recovery rates consistently run close to 90% which is a remarkable 30% improvement over recovery rates using activated carbon (Ramli, 2013).

Pre-cyanidation treatments are required for preg-robbing carbonaceous ores as the naturally occurring finely divided carbon in the ores acts in the same manner as the activated carbon introduced in the adsorption process with traditional CIL systems (Lewis, 1999). Preg-robbing is defined as the preferential absorption of gold-cyanide complex ions $[\text{Au}(\text{CN})_2^-]$ by organic carbon in the carbonaceous ore, that is the carbonaceous ore allows cyanide to dissolve gold but will reabsorb the solubilized gold onto the active carbon in the ore (Tretbar *et al.*, 2004).

PGM is currently trying to improve their processing system to maximize the recovery of fine gold in the carbonaceous gold ores as their gold grade gets poorer. This paper investigates the optimum process parameters for treatment of preg-robbing carbonaceous gold ores by conducting plant research on the resin-in-leach (RIL) method adopted by PGM. Data on the process parameters were collected during the first author's three-month practical work at PGM from December 2012 to February 2013 (Ramli, 2013).

PENJOM GOLD MINE (PGM), MALAYSIA

PGM, Malaysia commenced production in December 1996 as the largest open pit primary gold mine in Malaysia contributing to over 90% of the country's annual gold output and produces approximately 3,110,000 g of gold per annum (Malaysian Minerals, 2012). PGM is currently owned by J Resources Gold (UK) Ltd. As of June 2011, the gross resources and reserves were estimated to be 32,686,100 g and 18,224,600 g respectively, with a cut-off grade of 0.8 g/t. The expected life of mine is 6 years, i.e. from 2012 to 2017 (J Resources, 2012).

Geology

PGM lies within the central belt of Peninsular Malaysia which is characterised by a predominance of gold and base-metal mineralisation (Figure 1).

The lithological units of PGM (Figure 2) consist of a sequence of well-bedded tuffaceous siltstone, sandstone, pebble conglomerate, carbonaceous shale, calcareous shale-sandstone and minor limestone, belonging to the Permian Padang Tengku Formation of the Raub Group (Richardson, 1939; Lim *et al.*, 2001). The volcanoclastics and sedimentary sequence are cut by a microgranite and dacite intrusion, known locally as felsite. Within the mine area, the Penjom Thrust is the dominant feature. It is westward-

directed, strikes NE and dips to the SE. Considerable shear stresses along the Penjom Thrust have remobilized much of the carbon within the shale sequence to form a graphitic 'alteration' zone. Together with sheared and milled rock, this makes the Penjom Thrust an impermeable horizon (Lim *et al.*, 2001).

The gold mineralization occurs in quartz veins and sheared and lateral fault zones in the bedrocks which in some places are carbonaceous. Major structural trends are aligned N-S and NE-SW that controlled the gold mineralization. The style of mineralization is represented by widely-spaced sheeted gold-quartz-sulphide veins cutting the metamorphosed shales and volcanics (Hutchison, 2009).

Classification of Gold Ores

Rocks that have been identified to contain gold are isolated and categorized into 8 different stockpiles:

- run of mine, low carbon (RMLC)
- run of mine, high carbon (RMHC)
- low grade, low carbon (LGLC)
- low grade, high carbon (LGHC)
- sub-grade 75 mm
- sub-grade 25 mm
- boulder
- oxide ores

Ores containing high carbon is defined as organic carbon content of more than 0.5%. Run of mine is a mix of low, medium, and high grade ores to get a grade of approximately 2.0 g/t. Low grade ores are ores with a grade of less than 1.0 g/t. The minimum ore grade for processing in PGM is 0.8 g/t. Sub-grade ores are low grade, low carbon ores with a grade of 0.8-1.0 g/t. Boulders have an average grade of 1.0-1.5 g/t. The oxide ores have a grade of less than 1.0 g/t and contain no carbon. After going through the comminution circuit, the ground ore typically contains pyrite, galena, arsenopyrite, sphalerite, chalcopyrite, quartz, rock forming minerals, and carbonaceous materials together with Au, Ag, and base metals such as Cu, Zn, and Fe.

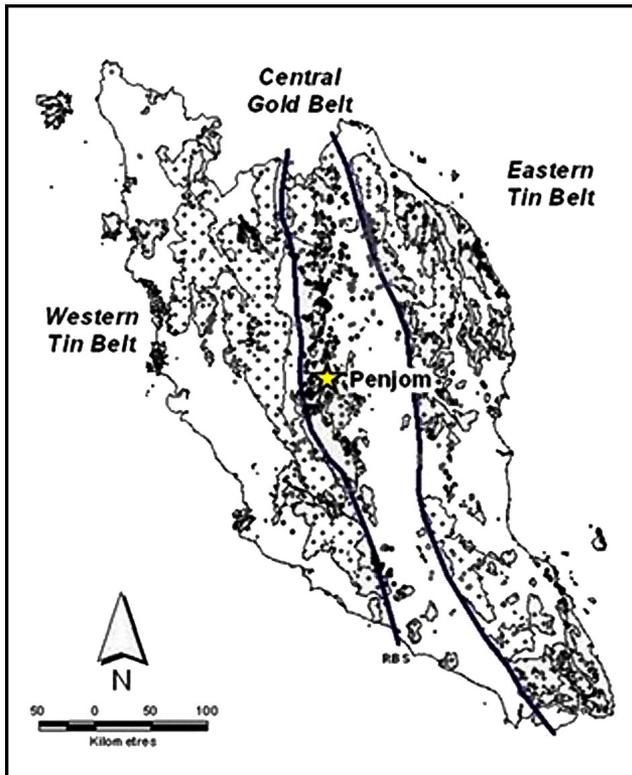


Figure 1: Map of Peninsular Malaysia showing the metallogenic belts and location of Penjom where PGM is located (Flindell, 2003).

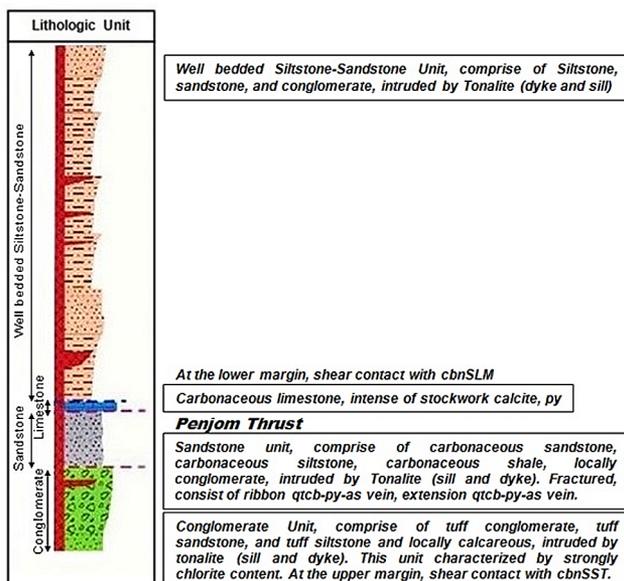


Figure 2: Lithological units of PGM (Image: courtesy of PGM).

Gold Processing Circuit

During the initial production, several design considerations for the processing circuit were taken into account such as invested budget, minimizing capital and operating costs, maximizing profit, minimizing risks, and government policies. The following factors were identified in causing low gold recovery and high operating costs: inefficient gravity and chemical process due to mineralogical conditions, preg-robbing gold ores, high operating costs of additional required processing units, and high costs in controlling and maintaining arsenic and cyanide Standard B effluent limits of 0.10 ppm as set by Malaysia's Environmental Law, Environmental Quality Act 1974, the Malaysia Environmental Quality (Sewage and Industrial Effluents) Regulations, 1979, 1999, 2000 (Water Treatment Resources, 2008).

PGM is the first processing plant outside the former Soviet Union to successfully use RIL technology for

primary recovery of gold in carbonaceous ores (DOWEX Ion Exchange Resins, 2003). The issue of recovering of gold interlocked in sulphide minerals is also addressed in various stages of the gold processing circuit. However, since the sulphide contents in PGM are low at less than 3 volume % (Lim *et al.*, 2001), it is not economical to liberate the gold interlocked in sulphide minerals by adding a roasting step. At present, it costs PGM approximately RM20 (US\$6.60) to produce 1 gram of gold (Mr. Mohd Izwan Mohd Puad, 2012, pers. comm., 18 December). Adding a roasting step will cost PGM approximately RM50 (US\$16.50) to produce 1 gram of gold, more than double the current cost.

Currently, PGM adopts the following processing design to recover gold from the ores (Figure 3):

- Comminution circuit – jaw crusher, semi-autogenous grinding (SAG) mill, and regrinding mill (RGM)
- Hydrocyclones
- Gravity concentration circuit – Knelson concentrator and shaking table
- Hydrometallurgy circuit – RIL tanks and RGM-RIL tanks
- Stripping columns
- Electrowinning cells
- Pyrometallurgy circuit – calcination and smelting

To address the issue of recovering fine gold from sulphide and carbonaceous ores, this paper emphasises on the processes in the hydrometallurgy circuit (blanking cells, resin-in-leach tanks, and regrinding mill – resin-in-leach tanks), stripping columns, electrowinning cells, and pyrometallurgy circuit (calcination, smelting, and gold bullion).

Blanking Cells

Ground ore in the form of slurry that exits as secondary cyclone overflow (SCOF) has a mesh of grind (MOG) of P95 75 µm (i.e. 95% passing 75 µm) whereas tertiary cyclone overflow (TCOF) has a MOG of P85 75 µm. Slurry from SCOF and TCOF is mixed with kerosene, a blanking agent, in blanking cells #1 and #2 respectively before entering the RIL tanks (Figure 4). Kerosene coats the carbonaceous ore to weaken the activeness of organic carbon (i.e. the carbon that causes preg-robbing) and passivates the adsorption surfaces on the carbon.

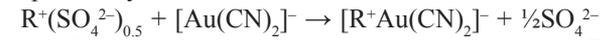
Retention time of slurry in both blanking cells is 27 minutes. Kerosene dosing in blanking cell #1 is more than in blanking cell #2 because SCOF contains higher organic carbon concentration and lower gold concentration than TCOF.

Other blanking agents that were tested for possible use in PGM are: diesel, sodium lauryl sulphate, cooking oil (palm oil, coconut oil, and corn oil), and fuel oil (high fuel oil, medium fuel oil, and low fuel oil). The blanking agent chosen should have the following properties: inexpensive, easily attainable, easily disposed, effective in weakening carbon, not dangerous, does not weaken the gold adsorption agent, low vapour pressure, does not affect the process, and not detrimental to the environment (Avocet Gold, 2004).

A low vapour pressure substance is required as substances with a high vapour pressure at normal temperatures are often volatile and will evaporate easily.

Resin-In-Leach (RIL) Tanks

Slurry mixed with kerosene from the blanking cell is passed through eight large RIL tanks which are 600 m³ each in sequence, and Minix-Dowex resins are passed in the opposite direction through the tanks. The resin beads are 500 to 700 µm in diameter and the total resin in the eight tanks is 40 g/L. Interstage screens that have an aperture of 400 µm are used to retain the resins in the RIL tanks and allow slurry to pass on to the next stage of RIL. Minix-Dowex resins have a functional group of SO₄²⁻. Extraction equation by the resins is as follow:



Other resins that were tested for possible use in PGM are Aurix resins and Purolite resins. Even though good gold recoveries were obtained using Aurix resins, it is more expensive than the Minix-Dowex resins. Purolite resins were found to absorb more copper than gold. Both Aurix and Purolite resins have a functional group of OH⁻.

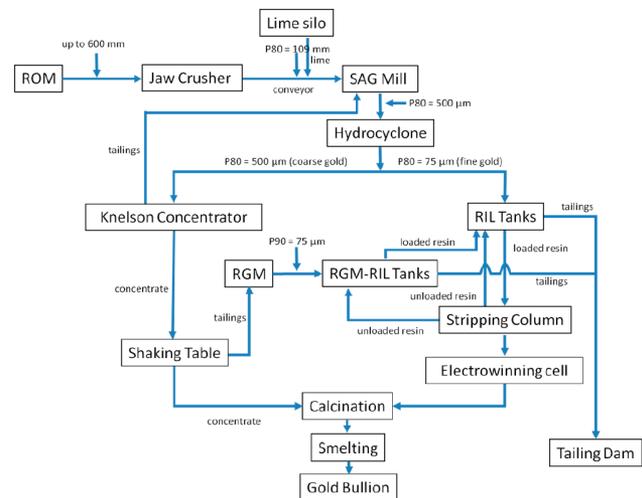


Figure 3: Simplified version of gold processing circuit in PGM.

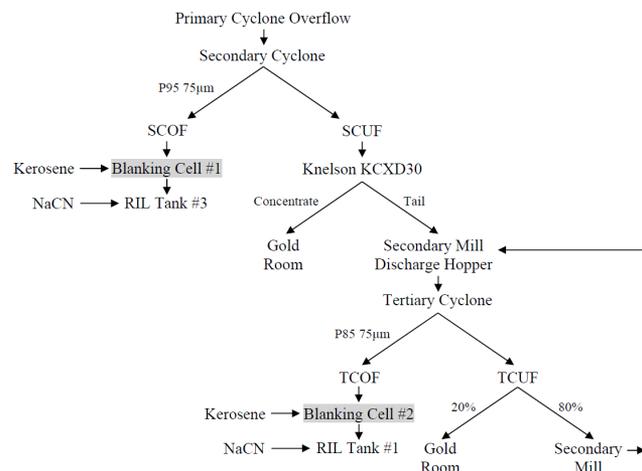


Figure 4: Flowsheet of hydrocyclones section in PGM.

Concentrations of cyanide used for leaching range between 230 and 280 ppm. Cyanidation involves the leaching of gold from its ores in a dilute sodium cyanide (NaCN) solution which is used to form cyanide complex ions with the Au, Ag, and base metals (Mohd Rozi *et al.*, 2011) in the presence of lime and oxygen. The temperature of the slurry in the RIL tanks is between 35° and 38°C (Mr. Ahmad Danial Hassan, 2013, pers. comm., 19 October). The pH of slurry in the RIL tanks are tested every 2 hours to ensure that pH of the slurry is between 10.5 and 11. Lime is added in blanking cells #1 or #2 if the pH level of the slurry in the RIL tanks is below 10.5. Total retention time of slurry in the RIL tanks is 36 hours.

The Au content in the metal-cyanide complex solution in the first feed tank is 1.5 g/t while at the outlet of the eighth tank, the Au content is 0.3 g/t because the resins have absorbed the Au-cyanide complex ions $[\text{Au}(\text{CN})_2^-]$ from the solution. The resins also absorbed Ag-cyanide complex ions and base metal-cyanide complex ions. All minerals (tailings) that are not absorbed by the resins in the RIL tanks, i.e. pyrite, galena, arsenopyrite, sphalerite, chalcopyrite, quartz, rock forming minerals, and carbonaceous materials flow in the form of slurry to the tailing pond.

Regrinding Mill–Resin-In-Leach (RGM-RIL) Tanks

In PGM, tailings from the shaking tables (gravity concentration circuit) are sent to the regrinding mill (RGM) before being fed into the regrinding mill–resin-in-leach (RGM-RIL) tanks to leach out the Au. The RGM is run by batch depending on the quantity of tailings from the shaking table. The purpose of this mill is to achieve fine grinding in order to liberate as much Au interlocked in the sulphide minerals as possible. PGM grinding size target is P90 75 μm . These very fine materials will also increase the leaching kinetic thus increasing the recovery rate in the RGM-RIL tanks.

The ground ores from the RGM are fed into the RGM-RIL circuit where it passes through five tanks. The operation

of the RGM-RIL tanks is almost similar to the RIL tanks. However, as ground ores from the gravity concentration circuit have a higher gold grade, the concentrations of cyanide and resins used in the RGM-RIL tanks are higher compared to those in the RIL tanks. Concentrations of cyanide used for leaching range between 1000 and 2000 ppm. Total retention time of slurry in the five RGM-RIL tanks is 48 hours. Figure 5 shows a schematic diagram of the RIL and RGM-RIL system in PGM.

Stripping Columns

Once the Au, Ag, and base metal content in the resins are close to 1000 ppm, the resins are said to have been loaded. The loaded resins are sent to the stripping columns where they are mixed with thiourea $[\text{SC}(\text{NH}_2)_2]$ and sulphuric acid. The purpose of the stripping stage is to strip the precious metal from the resin. The stripping stage is done at 60°C, and time required for the stripping process is 7 hours for loaded resin from RIL and 12 hours for loaded resin from RGM-RIL. The stripping time will lengthen if the temperature falls below 60°C. On the other hand, the resins will disintegrate at a temperature much higher than 60°C. Therefore, it is crucial to ensure temperature stays constant at 60°C.

Electrowinning Cells

Thiourea and sulphuric acid solution that contain Au-cyanide, Ag-cyanide, and base metals-cyanide complex ions from the stripping columns are fed into the electrowinning cells. The anode of the electrowinning cells is made of lead plates and the cathode is made of stainless steel wool. During electrowinning, Au, Ag, and base metals such as Cu, Zn, and Fe are deposited and accumulated at the cathode. The Au, Ag, and the base metals are washed down from the cathode by using high pressure water after 3 or 4 days. This process is known as “harvesting”. A flocculant, PA1753 is used to flocculate Au. The Au, Ag, and base metal slimes that were produced are manually collected, filtered, and sent for calcination.

Calcination

Gold slimes from the electrowinning cells and gold concentrates from the shaking tables are calcined separately. Gold bullions that will later be produced are labelled according to whether they were produced from gold slimes or gold concentrates. In PGM, the gold slimes and gold concentrates are roasted at setting temperature of 750°C (temperature range is from 720 to 760°C) to oxidise all the metals (except Au and Ag) from the gold slimes and all the sulphides from the gold concentrates. Any Au and Ag that are interlocked in the sulphide minerals will be released.

Smelting

The Au, Ag, and metal oxides from calcination of gold slimes and Au, Ag, and metal oxides from calcination of gold concentrates are sent for smelting. Four types of fluxes are used to remove the metal oxides as metal borosilicate slags:

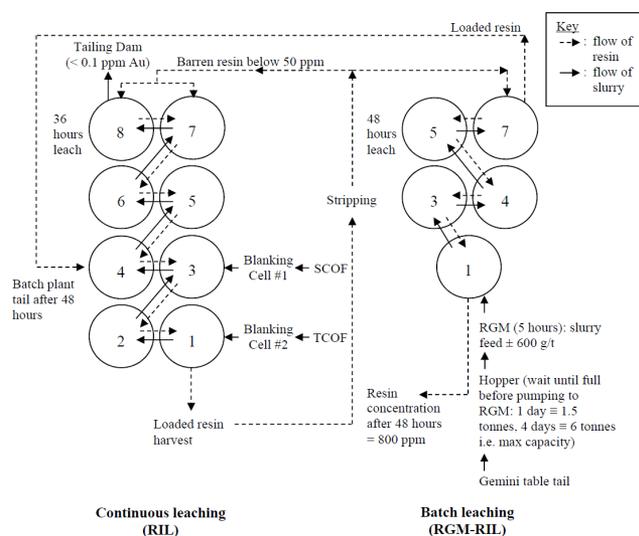


Figure 5: Leaching system in PGM.

- borax (anhydrous sodium tetraborate, $\text{Na}_2\text{B}_4\text{O}_7$) which is used to dissolve metal oxide and collects all contaminants to be sent back to SAG mill as slag
- silica (silicon dioxide, SiO_2) which reacts with metal oxide to form silicate that acts as an oxidizing agent to separate slag and gold
- nitre (potassium nitrate, KNO_3) which supplies oxygen for oxidation, and
- soda ash (sodium carbonate, Na_2CO_3) which is used as an oxidizing agent to speed up the dilution process for borax reaction.

Different gold sources, either from gold slime or gold concentrates require different flux combinations. The composition of flux that is added to the calcine gold is typically 70% borax, 30% silica, 15% nitre, and 10% soda ash.

Smelting is done in 2 hours at 1100°C. The composition of slag produced depends on the gold source. The following products are obtained after smelting: Au, Ag, and metal borosilicate slags. Interestingly, there are also base metals such as Cu, Zn, and Fe that have escaped oxidation and removal by the fluxes. The molten product is then poured into a mould and left to cool, forming a gold bullion. The cooled gold bullion is then soaked in nitric acid for 30 minutes to remove any impurities on the bullion.

Gold Bullion

Gold bullions produced by PGM weigh between 8 to 15 kg. The metallurgical compositions of these bullions are 80-85% Au, 10-15% Ag and 1-3% base metals such as Cu, Zn, and Fe. The bullions are sent to Perth Mint in Western Australia for refining to produce gold bullions with 99.99% purity before sending them to various banks.

PROCESS PARAMETERS

Major factors affecting the dissolution rate of gold are cyanide concentration, temperature, pH, surface area of gold exposed, and degree of agitation. This paper will only discuss the first three.

Cyanide Concentration

Although gold ore grade has decreased significantly over the last 10 years, the processing costs continue to rise. Table 1 shows that reagent make-up and dosing accounts for 1.4% of capital costs while Table 2 shows that reagents and chemicals accounts for 12.2% of operating costs. Warren *et al.* (1997) stated that as long as gold recovery is not compromised, reduced reagent consumption is a feasible method in reducing the costs of processing lower grade ores.

Since cyanide is a relatively costly reagent, a small decrease of cyanide dosage to the leaching circuit in the gold processing plant will result in a significant decrease of annual processing costs. This has led to an increase in research to determine the viability of reducing and optimizing cyanide consumption costs in gold extraction. Environmental concerns are also another factor that often dictate that cyanide concentration be kept as low as practically possible.

Table 1: Capital cost breakdown for a typical gold plant (Stange, 1999).

Item	% of Capital
General site facilities	7.4
Services facilities	7.5
General piping utilities	6.5
General electrical	4.8
Process control	1.1
Waste reclamation and delivery	0.9
Ore-delivery	2.7
Primary crushing	2.7
Ores storage	2.7
Milling	21.1
Thickening	5.1
Leaching	7.5
Adsorption	5.2
Elution	3.5
Gold refining	4.2
Reagent make-up and dosing	1.4
Residue disposal	1.0
Tailings dam	5.5
Indirects	9.2

Table 2: Operating cost breakdown for a typical gold plant (Stange, 1999).

Item	% of Operating
Reagents and chemicals	12.2
Consumables	16.2
Utilities	26.7
Maintenance	3.38
Labour	37.9
Tailings dam	0.8
Assays	2.8

Mudder & Gladstone (1989) believed that theoretically, due to the powerful leaching properties of cyanide and its ability to extract gold from complex chemical and mineral matrices, a free cyanide concentration as low as 100 ppm (parts per million) in solution is capable of achieving maximum rate and extent of gold dissolution. However, most cyanide leaching takes place with 0.1 kg NaCN/ton of ore and concentrations of cyanide range between 50 and 1000 ppm (Free, 2013). Figure 6 illustrates that maximum gold dissolution rate of 3.2 mg/in²/hr is achieved at 0.1% NaCN (i.e. 1.0 g/L NaCN or 1000 ppm). Cyanide consumption is increased if cyanicides (i.e. compounds such as iron and copper that complex with cyanide) are present. Otherwise, the cyanidation process will not have high recoveries due to competition of the other species for cyanide (Marsden and House, 2006).

Stability constant (also known as formation constant or binding constant) is an equilibrium constant for the formation of a complex in a solution and a measure of the interaction strength between reagents that form the complex. Due to the high stability constant of dicyanoaurate(I) complex ion, $\text{Au}(\text{CN})_2^-$ of 10^{37} M^{-2} (Rawashdeh-Omary *et al.*, 2000), it has a low dissociation tendency to produce gold and free cyanide

ions. This signifies that even a low cyanide concentration in the leaching circuit will readily dissolve gold and allow it to remain in solution without disassociating (Griffiths, 1988). A low concentration of free cyanide in solution results in a highly selective process and gold will preferentially dissolve over other metals that may be present in the ore. Concentration of cyanide is generally held in relative excess of minimum concentration required to avoid a loss in profits through uncovered gold being lost to tailings.

Temperature

The rate of gold dissolution increases with temperature as a result of the increased activities and diffusion rates of reacting species (Marsden & House, 2006). Figure 7 illustrates that by increasing the temperature from 25°C to 85°C, the rate of dissolution increase by 20%. However, this process will incur additional cost thus will only be used for leaching of high-grade materials. For the treatment of low-grade materials, ambient temperatures are applied.

Gold dissolution rate increases up to a maximum of about 85°C (Figure 7). The decrease of oxygen (i.e. the oxidant) solubility above this temperature offsets the benefits of increased ionic activity and diffusion rates of reacting species.

pH

Optimum pH range is important for process control as it affects the hydrolysis of cyanide and reaction kinetics.

Effect of pH on Hydrolysis of Cyanide

Gold-cyanide leaching reaction is always carried out in an alkaline environment, typically above pH 10 to minimize cyanide loss by hydrolysis (Free, 2013). The extent of dissociation reaction of hydrogen cyanide (a weak acid) at equilibrium as a function of pH is shown in Figure 8.

Cyanide leaching at low pH has been studied as a means to decrease the consumption of lime (or alkali). However, as pH decreases, the fraction of cyanide present in solution as hydrogen cyanide increases. Table 3 summarizes the percentages of hydrogen cyanide (HCN) and free cyanide (CN⁻) that exist in the total cyanide at different pH levels as shown in Figure 8.

Table 3: Amount of HCN and CN⁻ in total cyanide at different pH levels.

pH	%	
	HCN	CN ⁻
8.4	> 90	≤ 10
9.3	50	50
10.2	≤ 10	> 90

A high concentration of free cyanide is required for gold dissolution as HCN does not leach gold at a sufficiently fast rate to compete with the kinetics of leaching with CN⁻ (Marsden and House, 2006). Hence, a high pH (i.e. a low concentration of H⁺ ions) is required to minimize the extent of hydrolysis. The pH level is usually set between 10.5

and 11 to ensure approximately 95% of cyanide exists in the reactive CN⁻ form and less than 5% exists in the non-reactive HCN form. Hydrolysis will cause an increase of cyanide dosing to maintain gold leaching of gold leading to an increase of reagent costs. Also, at lower pH levels, cyanide hydrolyses to form poisonous hydrogen cyanide gas (H⁺+CN⁻ ⇌ HCN_(g)), which is colourless at room temperature and creates an occupational safety hazard.

Threshold exposure limit of hydrogen cyanide gas is 10 ppm (USEPA, 1981). Common symptoms of exposure include headache, nausea, and vomiting. Exposure of 100 ppm for an hour may lead to fatality (USEPA, 1981).

Effect of pH on Reaction Kinetics

Under normal conditions, gold cyanidation is optimized between pH 9.6 and 11 (Yannopoulos, 1991). Figure 9 illustrates that below pH 9.6 and above pH 11, rate of gold dissolution declines. Gold leaching is inhibited by lack of oxygen in the solution above pH 11.

According to Marsden & House (2006), the effect of pH on the rate of gold dissolution over pH 9.5 is small. In some cases, the rate of gold dissolution may decrease with increasing pH as a result of an increase in the rate of

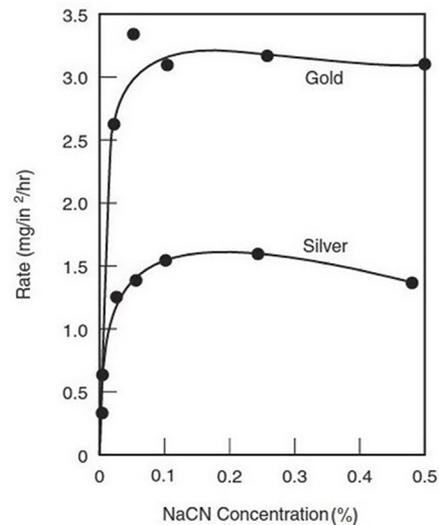


Figure 6: Effect of cyanide concentration on the dissolution rate of gold and silver (Marsden & House, 2006).

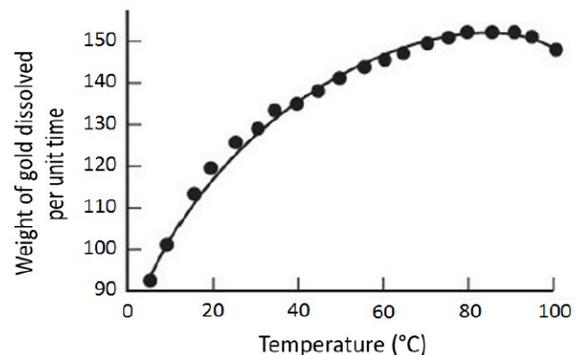


Figure 7: Effect of temperature on gold dissolution rate in aerated 0.25% KCN solution (modified from Marsden & House, 2006).

interfering reactions, such as dissolution of sulphides and other reactive species that also dissolve in dilute alkaline cyanide solutions. These interfering reactions consume cyanide and oxygen, producing solution species which can decrease the efficiency of gold leaching and recovery process.

In reality, other process factors usually govern the actual pH conditions applied, such as: dissolution rate of other ore constituents (copper, iron, tellurium, antimony, and arsenic minerals), which can negatively affect gold leaching; settling properties of slurry; slurry viscosity; cost of pH modification; and precipitation of solution species (calcium and iron). Due to these factors, optimum pH for leaching is different according to the type of leaching systems and ore types.

pH Modification and Control

Calcium hydroxide (slaked lime, $\text{Ca}(\text{OH})_2$) and sodium hydroxide are two alkalis that can be used for pH modification and control. Although sodium hydroxide is more soluble than slaked lime and is a highly effective dispersant, dissolution of ore constituents like silicates tend to form various solution species which can precipitate in undesirable forms and subsequently affect downstream processes (Marsden and House, 2006). Subsequently, slaked lime is more commonly used because it does not form undesirable precipitations and it is also cheaper. In order

to achieve the desired pH range for leaching, slaked lime concentrations of 0.15 to 0.25 g/L are typically required.

DISCUSSION

PGM, Malaysia is the first processing plant outside the former Soviet Union to successfully use resin-in-leach technology for primary recovery of gold in carbonaceous ores (DOWEX Ion Exchange Resins, 2003) through both resin-in-leach (RIL) and regrinding mill-resin-in-leach (RGM-RIL) circuits. Using carbon-in-leach (CIL) methods to process carbonaceous gold ores will yield very low gold recoveries.

CIL can considerably improve the extraction of gold from ores containing constituents that adsorb gold from leach solutions by introducing competing high activity carbon to preferentially adsorb gold that can be easily separated from the leach slurry. CIL is used together with kerosene (a blanking agent) in cases where carbon activity is not adequate to compete with the preg-robbing. However, the blanking agent fouls both the carbonaceous preg-robbing and the activated carbon which makes the process less effective than if ion exchange resins are used, as resins are less prone to organic fouling. Since PGM first employed the RIL process in place of the traditional CIL process, gold recovery rates consistently run close to 90% which is a remarkable 30% improvement over recovery rates using activated carbon.

Before being sent to the RIL tanks for leaching, the carbonaceous ore in PGM is first coated with kerosene to weaken the activeness of organic carbon (i.e. the carbon that causes preg-robbing) and passivate the adsorption surfaces on the carbon. Retention time of slurry undergoing leaching in agitated tanks vary in different processing plants and can range from a few hours to a few days. Retention time of slurry in the RIL tanks is 36 hours whereas the retention time in the RGM-RIL tanks is 48 hours.

Process parameters that determine the recovery of gold are: cyanide concentration, temperature, pH, surface area of gold exposed, and degree of agitation, but in this paper, only the first three is discussed. PGM uses the following process parameters in the RIL and RGM-RIL tanks to recover gold from carbonaceous ore: cyanide concentration between 230 and 280 ppm in RIL tanks, and between 1000 and 2000 ppm in RGM-RIL tanks; slurry temperature between 35 and 38°C; and pH level between 10.5 and 11.

Different concentrations of cyanide used in leaching have been tested by the metallurgists in PGM since operations first commenced. Cyanide concentration of up to 330 ppm was previously used in the RIL tanks but more recently, the concentration was reduced to as low as 230 ppm. This reduction was done when it was found that gold is still able to be sufficiently leached at this concentration. Subsequently, the reduced reagent consumption reduces the annual costs of processing while still maintaining high gold recoveries. Very high concentrations (between 1000 and 2000 ppm) of cyanide are used in the RGM-RIL tanks because the feed of RGM-RIL tanks is the tailings from the

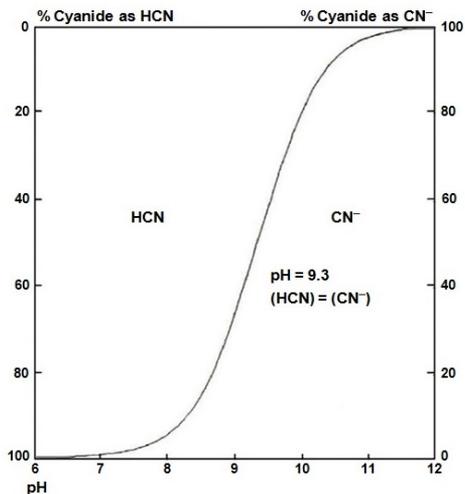


Figure 8: Speciation of cyanide and hydrogen cyanide in aqueous solution as a function of pH (modified from Griffiths, 1988).

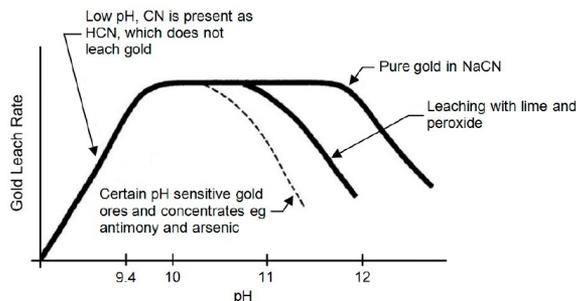


Figure 9: Gold leach rate vs pH (Yannopoulos, 1991).

shaking tables (gravity concentration circuit) which has very high grade of gold, i.e. as high as 600 g/t.

Although slurry is not preheated before entering either the RIL or the RGM-RIL tanks, the slurry temperature in both leach tank circuits is between 35° and 38°C. This is due to the heat generated by the semi-autogenous grinding (SAG) mill and regrinding mill (RGM), i.e. kinetic energy is converted to heat energy. In the SAG mill, the feed and discharge end trunnion bearing temperature is set to a maximum of 60°C, and the feed and discharge end pinion bearing temperature is set to a maximum of 75°C. Only these temperatures are monitored by PGM plant operators. As the slurry flows through the processing circuit (i.e. from SAG mill to the hydrocyclones and blanking cells) to the RIL tanks, the temperature decreases from between 60° and 75°C to between 35° and 38°C.

Care is taken to maintain the level of pH between 10.5 and 11 to minimize cyanide loss by hydrolysis and optimize rate of gold dissolution. The pH of slurry in the RIL and RGM-RIL tanks at PGM is tested every 2 hours to ensure that pH is between 10.5 and 11. If pH level of the slurry is less than 10.5, lime is added to increase the pH. Method of adding lime into the tanks differs between the leaching circuits. In RIL tanks, lime is added in the two blanking cells but in RGM-RIL tanks, the lime is added straight into the tanks.

FUTURE WORK RECOMMENDATIONS

PGM is currently trying to improve their processing system to maximize the recovery of very fine gold in the carbonaceous gold ores as their gold grade gets poorer. To optimize process parameters, the author recommends the followings:

Further work on reducing the cyanide consumption should be done. Since cyanide is a relatively costly reagent, a small decrease of cyanide dosage to the leaching circuit in the gold processing plant will result in a significant decrease of annual processing costs. Theoretically, due to the powerful leaching properties of cyanide and its ability to extract gold from complex chemical and mineral matrices, a free cyanide concentration as low as 100 ppm in solution is capable of achieving maximum rate and extent of gold dissolution.

Work on finding the optimum temperature for gold dissolution without incurring additional cost should also be done. The rate of gold dissolution increases with temperature due to the increased activities and diffusion rates of reacting species (Marsden and House, 2006). PGM does not monitor the temperature of the slurries in the RIL and RGM-RIL tanks which fluctuates since the temperature of slurry exiting the mills are not constant. The gold grade in the RIL tanks is relatively low, i.e. an average of 1.5 g/t and hence, ambient temperature may theoretically be used without causing a negative effect to the process. However, work should be done to test if cost incurred by preheating the slurry before entering the leaching circuit is justified by the increase of rate of gold dissolution.

In addition, to improve and maximize gold recovery, the author recommends the followings:

At present time, PGM does not test or monitor the salinity and total dissolved solids (TDS) in process water. The author recommends that process water is tested to see how salinity and TDS affects the treatment process of recovering gold from carbonaceous ores. Necessary steps should be taken to reduce the salinity and TDS content to further optimize the gold recovery process.

The tailing dam at PGM has a capacity of 4.3 million tonnes and approximately 500 g of gold that “escapes” leaching process is discharged daily. The tailing dam contains approximately 40% preg-robbing materials, 20% sulphides, 20% silicates, 10% gold, and 10% “others”. Work should be done to test ways on how the gold from the tailing dam can be economically mined which will effectively increase the current expected mine life of 6 years.

CONCLUSIONS

The geology of PGM is such that gold is mineralised in quartz veins together with sulphide minerals and organic carbon in the ores. The sulphide contents in PGM are however low, i.e. less than 3 volume %.

This paper demonstrates the success of the resin-in-leach (RIL) process in recovering gold from carbonaceous gold ores. By using RIL technology, carbonaceous gold ores can successfully be processed as demonstrated by PGM, Malaysia. PGM uses the following process parameters to achieve maximum gold recoveries: cyanide concentration between 230 and 280 ppm in RIL tanks, and between 1000 and 2000 ppm in RGM-RIL tanks; slurry temperature between 35° and 38°C; and pH level between 10.5 and 11.

To maximize the recovery of fine gold in the carbonaceous ore with minimal cost, PGM should carry further work on optimizing cyanide consumption and reaction temperature in the leach tanks. The salinity and total dissolved solids content of process water should also be tested to see how the treatment process of recovering gold from carbonaceous ores is affected. In addition, efforts should be made to re-mine the gold that “escaped” into the tailing dam.

PGM is a good example that the RIL process can be adopted to overcome the biggest problem of inefficiency in using activated carbon to adsorb gold. Gold recovery process at PGM is highly efficient while maintaining low operating costs of RM20 (US\$6.60) to produce 1 gram of gold. This “state-of-the-art” RIL system which is used in PGM for the past 12 years should be used by other processing plants around the world that are working with preg-robbing gold ores.

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