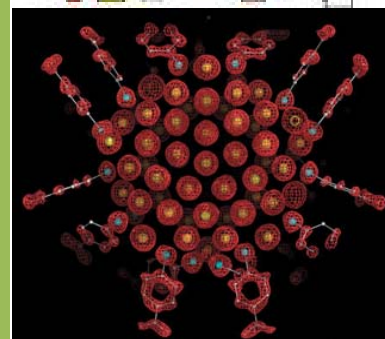# Gold Extraction and Recovery Processes

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Executive Summary

Various methods such as gravity concentration, flotation, panning, pyrometallurgy, cyanidation etc are available for the extraction of gold metal from its ores. Amongst these methods, cyanidation is the most common method used in the leaching of gold from the ore. This process involves the dissolution of gold containing ores in dilute cyanide solution in the presence of lime and oxygen. For refractory ores such as sulfide ores and carbonaceous ores which are not susceptible to direct cyanide leaching, various methods such as pressure oxidation, roasting, chlorination, biooxidation etc are available to treat these ores to expose the gold particles before cyanidation. Thioura leaching was developed as a potential substitute to cyanide leaching due to its lower toxicity and greater rate of gold and silver dissolution. Other alternative lixiviants to cyanide such as bromides (acid and alkaline), chlorides and thiosulfate are also being developed.

The common processes for recovery of gold solution includes: (i) Carbon adsorption, Merrill-Crowe process, (iii) electrowinning and (iv) ion-exchange / solvent extraction. Traditionally, Merrill-Crowe process was used to remove gold from a cyanide solution by using zinc dust to precipitate gold from its solution. Carbon adsorption is increasing using in newer plants for gold recovery. Carbon in Pulp (CIP) technique involves contacting the leached pulp with granular carbon in a series of agitating tanks with a sufficient retention time.

Selected summary of patented gold recovery processes and examples of commercial mining and recovery gold processes are also provided in this report.

Introduction

Gold has been known and highly valued since prehistoric times. It may have been the first metal used by humans and was valued for ornamentation and rituals [1]. Approximately 60% of the gold mined today is held by government and central banks and gold is presently the most significant means of international payment [2].

Production and Reserves

Annual world production of gold has been steadily increasing over the years reaching approximately 2,300 metric tonnes in recent years. Based on Table 1, China, South Africa, Australia and United States are the largest producers of gold with a total production of approximately 42% of the world's supply. Gold abundance in the Earth's crust is 0.002 per 10^6 atoms of silicon [2]. Gold average economic abundance in the ore today is in the range of 0.1 to 0.2 oz/ton or 3.42-6.84 ppm, but deposits yielding grades to the fire assay which are as low as a tenth of those values are also exploited [2]. It may be noted that gold distributions tend to be highly irregular on macro as well as micro levels.

Table 1 Distribution of gold production and reserves according to countries

	Mine production		Reserves [1]	Reserve base [2]
	2007	**2008**[e]		
United States	238	230	3,000	5,500
Australia	246	225	5,000	6,000
Brazil	40	40	2,000	2,500
Canada	101	100	2,000	4,200
China	275	295	1,200	4,100
Chile	42	42	2,000	3,400
Ghana	84	84	1,600	2,700
Indonesia	118	90	3,000	6,000
Mexico	39	41	1,400	3,400
Peru	170	175	1,400	2,300
Papua New Guinea	65	65	1,300	2,300
Russia	157	165	5,000	7,000
South Africa	252	250	6,000	31,000
Uzbekistan	85	85	1,700	1,900
Other countries	471	440	[8]10,000	[8]22,000
World total (rounded)	2,380	2,330	47,000	100,000

Source: USGS, Mineral Commodity Summaries, Jan 2009

[1] **Reserves —** That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative.
Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system

[2] **Reserve Base —**That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the inplace demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics.
The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). The term "geologic reserve" has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve-base category; it is not a part of this classification system.

Gold Minerals

In nature, gold most often occurs in its native state (that is, as a metal), though usually alloyed with silver. Native gold contains usually eight to ten percent silver, but often much more — alloys with a silver content over 20% are called electrum [1].

The average concentration of gold in the world is about 0.005 g/t which is lower than other metals. The low concentration of gold in primary rocks means that upgrading by a factor of 3000-4000 is usually required during ore formation processes to achieve commercial concentrations. This may be possible using natural gravity concentration processes or leaching gold with natural fluids from the host rock. Thus, by highly oxidizing, acidic and complexing (chloride) solutions, followed by redeposition in a more concentrate form. Owing to its siderophile properties (weak affinity for oxygen and sulfur, high affinity for metals) gold tends to concentrate in residual hydrothermal fluids and subsequent metallic or sulphidic phases, rather than silicates, which form at an early stage of magma cooling. Rocks that are high in clays and low in carbonates are the best sources of gold, and reprecipitation occurs when the hydrothermal solutions encounter a reducing environment, such as a region of high carbonate, carbon or reducing sulphide contain [3].

The various types of common gold deposits are tabulated in Table 2 [2].

Table 2 Gold deposits

Deposit	Structural character	Age	Type locality	Main minerals	Assoc. minerals	Typical elements	Metals mined	% of world production
Gold-quartz lodes	Hydrothermal veins	Mostly precambrian	To be expected in precambrian rocks, such as the Canadian, Australian, Brazilian-Guayana and African-Arabian shields	Low-silver native Au	Quartz	Si	Au	20-25
Epithermal deposits	Hydrothermal veins	Tertiary	Emperor deposit (Fiji)	High-silver native Au, tellurides	Quartz, carbonate, barite, fluorite	Te, Bi, Pb, As, Sb, Hg, etc.	Au, Ag, some base metals	Very small
Young placers	Unconsolidated or semiconsolidated sands and gravels	Recent	River beds that assay for gold	Native Au	Heavy minerals such as monazite, ilmenite, zircon, apatite, pyrochlore, etc	Ti, RE's, Nb	Au, Ti, RE's, Nb	5-10; 25 to 35 in the past
Fossil placers	Conglomerates consisting of quartz pebbles in matrix of pyrite and mica	Precambrian	Witwatersrand To be expected in the precambrian shields	Native Au	Heavy minerals including uraninite	U, PGE, etc	Au, U, PGE	More than 60
Disseminated gold	Silty carbonaceous dolomitic limestone	Mesozoic tertiary	Carlin, Cortez, Getchel, Gold Acres (Nevada type ores); Bald Mountain	Very fine native Au	Silicate, barite, pyrite and other sulfides	Fe, As, Sb, Hg, C, very little Ag	Au	Has been increasing. Brought into prod. In 1935

Greenstones	Metamorphosed volcanic	Precambrian	Kalgoorlie, Hemlo, Timmins, Val D'Or Kirkland Lake	Native Au, calaverite	Tellurides of Au, Hg, Pb, Cu, Bi, compounds of gold with Hg, Sb, and other elements, native tellurium	Hg, Pb, Bi, Sb	Au	Has been increasing
Young greenstones	Metamorphosed volcanic	Mesozoic tertiary	Deposits in Southeastern Au California	Native Au	Pyrite, Fe oxides, various silicates	Fe, Si	Au	Has been increasing
Byproduct gold		-	Any gold bearing base metal deposit	Native Au, other gold minerals	Base metal minerals	Cu, Pb, Zn, As, Sb, Bi	Au, base metals	5-10
Gold in seawater	0.0011-0.05 ppb in solution	-	-	-	-	-	-	-

Gold Extraction Methods

Although new process are being proposed on a regular basis, there have in fact been no dramatic changes in the metallurgical techniques for gold extraction since the introduction of the cyanide process (cyanide leaching or cyanidation) by McArthur and Forrester in 1887 [2]. A basic flowchart for the recovery of gold from its ore is provided in Figure 1.
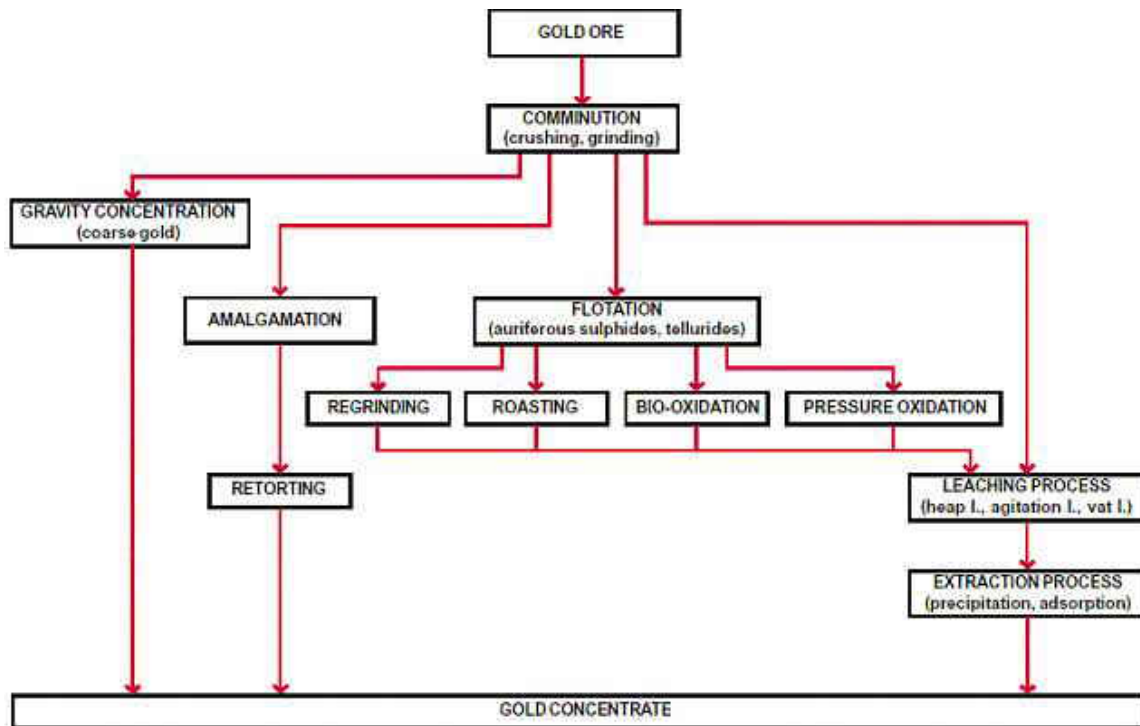

Figure 1 Basic flowchart for gold recovery.

The major categories of commercially viable recovery processes include the following [4, 5]:

1. Amalgamation (with mercury)
2. Gravity Concentration (using jogs, tables, spirals, Reichert cone, moving belt separator, etc.)
3. Flotation (as free particles or contained in base metal sulfide concentrates)

4. Pyrometallurgy (in the smelting and refining of base metal ores and concentrates)
5. Hydrometallurgy (direct cyanidation, cyanidation with carbon adsorption, heap-leach and chlorination-leach)
6. Refractory ore processing
7. Alternative lixiviants

Amalgamation

This is an ancient process which involves the alloying of the gold particles with metallic mercury to form amalgam and then the separation of the gold from the mercury by heating in retorts until the mercury is distilled off. The method is used for the treatment of coarser gold (30 microns in diameter or greater) [2]. This process is strongly out of favor with the major mining companies, due to the extremely toxic nature of mercury and the processes inferior performance when compared to the available alternatives. The process is still used extensively by artesian mines in third world countries and at small mines, due to its simplicity [4].

Gravity Concentration

Gravity concentration processes rely on the principal that gold contained within an ore body is higher in specific gravity than the host rocks that contain the gold [4]. Elemental gold has a specific gravity of 19.3, and typical ore has a specific gravity of about 2.6. All gravity concentration devices create movement between the gold and host rock particles in a manner to separate the heavy pieces from the lighter pieces of material.

Panning is probably the oldest technique used for the recovery of gold. Panning is a type of gravity concentration used by prospectors for the recovery of gold from river beds. It concentrates the heavy gold particles at the bottom of the pan while the light gangue is washed off on top [2].

Flotation

The flotation process consists of producing a mineral concentrate through the use of chemical conditioning agents followed by intense agitation and air sparging of the agitated ore slurry to produce a mineral rich foam concentrate [4]. The process is said to have been invented by a miner who watched the process happening while washing dirty work clothing in his home washing machine.

Specific chemicals are added to either float (foam off) specific minerals or to depress the flotation of other minerals. Several stages of processing are generally involved with rough bulk flotation products being subjected to additional flotation steps to increase product purity.
The flotation process in general does not float free gold particles but is particularly effective when gold is associated with sulfide minerals such as pyrites. In a typical pyrytic gold ore, the gold is encapsulated within an iron sulfide crystal structure. Highly oxidized ores generally do not respond well to flotation.
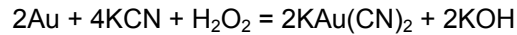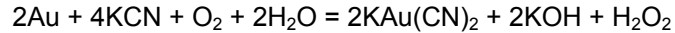
Advantages of the flotation process are that gold values are generally liberated at a fairly coarse particle size (28 mesh) which means that ore grinding costs are minimized. The reagents used for flotation are generally not toxic, which means that tailings disposal costs are low.

Flotation will frequently be used when gold is recovered in conjunction with other metals such as copper, lead, or zinc. Flotation concentrates are usually sent to an off-site smelting facility for recovery of gold and base metals.

Cyanide leaching is frequently used in conjunction with flotation. Cyanidation of flotation concentrates or flotation tailings is done depending upon the specific mineralogy and flowsheet economics.

Cyanide Process

It is the most common used process for gold extraction. This process involves the dissolution of gold (and of any silver present in soluble form) from the ground ore in a dilute cyanide solution (usually NaCN or KCN) in the presence of lime and oxygen according to the reactions [2,5]:

$$2Au + 4KCN + O_2 + 2H_2O = 2KAu(CN)_2 + 2KOH + H_2O_2$$

$$2Au + 4KCN + H_2O_2 = 2KAu(CN)_2 + 2KOH$$

Elsner's equation $4Au + 8CN^- + O_2 + 2H2O \rightarrow 4Au(CN)_2^- + 4OH^-$

With optimum cyanide concentration (about 0.05% NaCN), clean gold particles dissolve at a rate of 3.25 mg per sq cm per hour while for silver the rate is about one-half that of gold. Therefore , coarse gold particles (larger than 100 mesh) are usually removed by gravity concentration methods before cyanidation. In general, cyanidation process consists of percolation or agitation leaching of gold and silver ores with dilute cyanide solution, generally less than 0.3 percent sodium cyanide. In plant practice the addition of lime to a cyanide pulp is universal to prevent hydrolysis and to neutralize any acidic constituents present in the ore. Additional advantages of lime addition include decomposition of bicarbonates in mill water, improvement in settling rate in counter current decantation thickeners and improvement in extraction rates for certain types of ores such as tellurides and ruby silver.

Heap Leaching

Heap leaching was introduced in the 1970's as a means to drastically reduce gold recovery costs. This process has literally made many mines by taking low grade geological resources and transforming them to the proven ore category. Ore grades as low as 0.01 oz Au per ton have been economically processed by heap leaching [4].

Heap leaching involves placing crushed or run of mine ore in a pile built upon an impervious liner. Cyanide solution is distributed across the top of the pile and the solution percolates down through the pile and leaches out the gold. The gold laden pregnant solution drains out from the bottom of the pile and is collected for gold recovery by either carbon adsorption or zinc precipitation. The barren solution is then recycled to the pile.

Heap leaching generally requires 60 to 90 days for processing ore that could be leached in 24 hours in a conventional agitated leach process. Gold recovery is typically 60-80% as compared with 85-95% in an agitated leach plant. Even with this inferior performance, the process has found wide favor, due to the vastly reduced processing costs compared with agitated leaching.

The cost advantages are as follows:

1. Comminution: Where as heap leaching is typically done on –3/4 inch rock, agitated leaching requires reduction to –200 mesh. This additional step is typically done with large grinding mills that consume roughly one horsepower per ton per day of capacity.
2. Solids liquid separation steps are not required for heap leaching.
3. Tailings disposal costs are quite high for a modern agitated leach plant. Large expensive liquid containment dams are required. By comparison, heap leach pads can generally be left in place after reclamation.

Disadvantages, in addition to lower recovery of heap leaching compared with agitated leaching, include:

1. The stacked ore must be porous enough to allow solution to trickle through it. There have been many recovery failures due to the inability to obtain solution flow. This is widely

experienced when ores have a high clay content. This problem is often alleviated by agglomeration prior to heap stacking.

2. In areas of high rainfall, solution balance problems can arise, resulting in the need to treat and discharge process water.
3. In extremely cold areas, heap freezing can result in periods of low recovery. Operational procedure modifications such as subsurface solution application have reduced, but not eliminated, this concern.
4. Ice and snow melting can result in excessive accumulation of leach solutions. This concern can often be mitigated by use of diversion structures.

Quite frequently, mines will use agitated leaching for high grade ore and heap leaching for marginal grade ores that otherwise would be considered waste rock. A common recovery plant is often employed for both operations.

Table 3 Heap and dump leaching practices in USA

Mine/Operator	Reserves (000's)	Grade (oz/t Au)	Capacity (stpd)	Type Operation	Recovery (%)
Maggie Creek, Newmont	3,600	0.049	2,000	Uncrushed-aggl.-dump-CA-EW	45
Gold Quarry	90,000	0.035	20,000	Uncrushed-dump-CA-EW	45
Zortman/Land-Pegasus	28,000	0.035	16,000	Uncrushed-dump-MC	50
Relief Canyon-Lacana	9,200	0.032	4,000	Uncrushed-heap-CA-EW	50
Pinson-Pinson Mining	2,200	0.025	1,500	Uncrushed-heap-CA-EW	60
Prebble-Pinson Mining	1,800	0.062	1,000	Uncrushed-heap-CA-EW	40
Borealis-Tenneco	2,000	0.090	2,500	-1"-Aggl.[a]-heap-MC	70
Alligator Ridge-Amelsco	3,000	0.070	3,000	-3/4"-Aggl.[a]-heap-CA-EW	80
Ortiz-Goldfields	7,100	0.053	3,500	-3/8"-Aggl.-heap-CA-EW	80
Round Mt.-Smoky Valley	200,000	0.037	18,000	-3/8"-heap-CA-EW	75
Northumberland-Cyprus	16,000	0.050	4,000	-5/16"-Aggl.-heap-CA-EW	70

MC: Merrill-Crowe CA: Carbon Adsorption EW: Electrowinning
a Agglomeration with lime or cement and cyanide

Refractory Ore Processing

The common definition of "refractory" gold ores, are those ores that do not allow the recovery of gold by standard gravity concentration or direct cyanide leaching. Typical refractory ores include:

(i) Gold is very finely disseminated or is present in solid solution in sulfide matrix, mostly pyrite, pyrrhotite and arsenopyrite.
(ii) Gold associated with tellurides.
(iii) Gold/silver values are contained in base metal sulfides of lead, copper and zinc.
(iv) Gold is present in carbonaceous ores.
(v) Silver is very finely disseminated in the gangue matrix, mostly quartz or complexed with manganese oxides.

With many sulfide ores, the ore cannot practically be ground down fine enough to expose the gold particles. For cyanide to leach gold, the cyanide solution must come into direct contact with gold molecules. The objective of pretreatment (by roasting) for these ores is to remove enough of the sulfide so that at least a small portion of all gold particles are directly exposed, making them amenable to cyanidation. Processes available for treatment all involve oxidation of sulfur to form water soluble sulfates or sulfur dioxide. The main sulfur oxidation processes include:

1. **Pressure oxidation**: Utilizes oxygen and heat under pressure in a liquid medium, to effect oxidation of sulfur by way of a controlled chemical reaction. High pressure autoclaves are used for the reactors. Reactor operation is under alkaline or acidic conditions, depending upon the specific process. The oxygen overpressure required is primarily determined by the mass transfer requirements of the process and higher overpressures tend to shorten the reaction rate and thus the residence time [5].
2. **Bio-oxidation**: Bio-oxidation uses sulfur consuming bacteria in a water solution to remove sulfur. Biological oxidation of sulfide minerals is carried out by the bacterium Thiobacillus Ferrooxidans under optimum conditions (pH = 2 and 30°C) [5]. Advantages of this process include use of air instead of oxygen and normal atmospheric operating conditions. Disadvantages include long retention time (may range from 15 hours to 150 hours) due to slow bacterial oxidation rate, cooling required due to exothermic nature of reaction and addition of lime to adjust pH in the range 1 to 2.
3. **Roasting**: Roasting uses heat and air to burn away the sulfur from dry ore. Roasting was the standard method for sulfur oxidation years ago when it was considered environmentally acceptable to emit large quantities of sulfur dioxide gas into the atmosphere. Today's roasting plants employ elaborate gas scrubbing systems that frequently produce sulfuric acid as a byproduct.
4. **Chemical oxidation** using nitric acid at ambient pressure and temperature has also been used on a limited basis.

Carbonaceous ores that allow cyanide to dissolve gold but quickly adsorb gold back onto the active carbon in the ore. Treatment processes include chlorination for carbon deactivation, roasting to burn away carbon and carbon-in-leach which introduces competing high activity carbon to preferentially adsorb gold that can be conveniently separated from the leach slurry.

Gold ores containing copper and zinc require uneconomically high quantities of cyanide to process due to the solubility of copper and zinc in cyanide. In practice, to avoid excessive cyanide consumption by copper and zinc, the roasted alcine is usually acid leached to dissolve copper and zinc prior to cyanidation [5]. Ores containing gold tellurides may also be effectively treated effectively by a combination of roasting and cyanidation [5].

It should be noted that most of the refractory ore treatment processes are expensive and frequently economical only with higher grade ores and high processing rates.

Thiourea leaching

This method was developed as a potential substitute for cyanidation (of gold as well as silver). Thiourea's lower toxicity and greater rate of gold and silver dissolution compared to cyanide give it an advantage in reaching commercial application before other non-commercial lixiviants [2]. Alternative lixiviants include bromides (acid and alkaline), chlorides and thiosulfate. The lower sensitivity to base metals (As, Pb, Cu, Sb, Zn) or impurities render possible the use of this process on many refractory gold ores. Thiourea leaching has been tried on different materials and ores with success. Pre-roasted materials were leached with gold extractions up to 99 per cent with leaching time as short as 30 minutes. Recovery of gold from pyrite and chalcopyrite concentrate has given 96 per cent extraction. Extraction of 90 per cent is reported on carbonaceous material. Commecial application of thiourea in the extraction of gold is performed in Australia on antimony concentrate, on carbonaceous concentrate in China and in roasted zinc ores in France.

The major concern in thiourea leaching is the degradation of the reagents. Uncontrolled oxidation of thiourea not only leads to loss of reagent but also the formation of elemental sulfur which covers the gold particles and prevents its leaching [5]. The dissolved precious metals from pregnant solution can be recovered by suitable adsorptions such as activated carbon, strong acid cation exchangers and thio/resins or using electrowinnig, cementation and gaseous reduction [5]. Most of the work done to recover gold with thiourea is on the leaching part of the process. Few results are available on the recovery of gold and silver from the pregnant solution [2].

Gold Recovery from Solution

The common processes for recovery of the solubilized gold from solution are (certain processes may be precluded from use by technical factors) [5,6]:

- Carbon Adsorption
- Merrill-Crowe process
- Electrowinning
- Ion-exchange/Solvent Extraction

(i) *Carbon Adsorption*

The process known as **carbon in pulp**, or charcoal in pulp or CIP controls the gold precipitation from the cyanide solution by use of activated charcoal (carbon). Activated carbon can be manufactured from wood, nuts shells, coal, petroleum coke and a variety of organic products. Coconut shell carbon is preferred because of its commendable durability and high adsorption capability for gold and silver cyanide [5]. Other modifications include Carbon-in-Leach (CIL) and Carbon-in-Column (CIC).

The technique involves contacting the leached pulp with granular carbon (about -8 to +20 mesh) in a series of gently agitating tanks with a sufficient retention time [2]. The carbon is recycled through the circuit to build up the loading to 8-10 per cent by weight. The loaded charcoal is then separated from the pulp on a suitable vibrating screen, coarse enough to retain the carbon, but fine enough to allow the pulp to pass through. The carbon is next sent to the stripping column for desorption and regeneration. The technique is used on low grade gold and silver ores.

Leached pulp and carbon are transferred in a counter current flow arrangement between a series of tanks, usually numbering 4 to 6 [1] as shown in Figure 2. In the final tank, fresh or *barren* carbon is put in contact with low grade or tailings solution. At this tank the fresh carbon has a high activity and can remove trace amounts of gold (to levels below 0.01 mg/L Au in solution).

As it moves up the train, the carbon loads to higher and higher concentrations of gold, as it comes in contact with higher grade solutions. Typically concentrations as high as 4000 to 8000 grams of gold per tonne of carbon (g/t Au) can be achieved on the final loaded carbon, as it comes in contact with freshly leached ore and pregnant leach solution (PLS). This can be measured by comparing the amount of gold extracted from the carbon to the amount of carbon used. The final loaded carbon then is removed and washed before undergoing "elution" or desorption of gold cyanide at high temperature and pH. Hot caustic-cyanide (1%NaOH, 0.1 to 0.2%NaCN) solution at nearly boiling temperature in 36 to 72 hours [5]. The elution rate may be accelerated by adding 10% alcohol at temperatures around 60 to 80°C with a stripping time of 4 to 6 hours. The elution of loaded carbon may also be speeded by using pressure elution (120 to 130°C at 70 psig) in 6 to 8 hours [5].
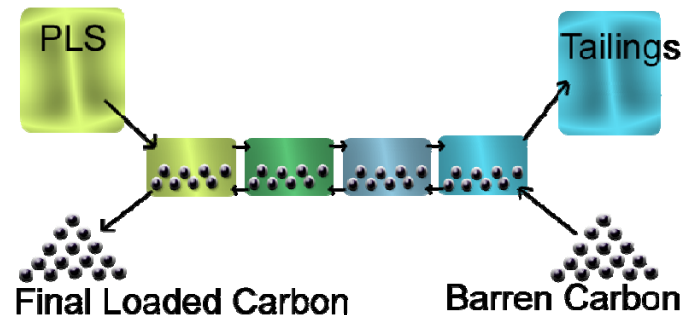
Figure 2 Process flow for carbon in pulp [1].

The rich eluate solution that emerges from the elution process is passed through electrowinning cells where gold and other metals are precipitated onto the cathodes. After precipitation, the product is treated with dilute sulfuric acid to dissolve residual zinc and most of the copper (if any is present) [2]. The residual is washed, dried and melted with fluxes. The remaining gold and silver alloy, called *dore'*, is cast into molds for assay. Refining is accomplished by electrolysis during which silver and any platinum group elements are also separated and recovered. Another method of separating gold from silver dore' is by parting, where hot concentrated sulfuric or nitric acids are used to differentially dissolve the silver, while the gold is recovered from the residue.

(ii) Merrill-Crowe process

The Merrill-Crowe Process is a separation technique for removing gold from a cyanide solution. The solution is separated from the ore by methods such as filtration and counter current decantation (CCD) and is then clarified in special filters, usually coated with diatomaceous earth to produce a clarified solution [6]. Oxygen is then removed by passing through a vacuum deaeration column. Zinc dust is then added to the clarified, deaerated solution which precipitates the gold because zinc has a higher affinity for the cyanide ion than gold.

Gold (along with silver) is then precipitated with zinc dust according to the reaction:

$$2KAU(CN)_2 + Zn = K_2Zn(CN)_4 + 2Au$$
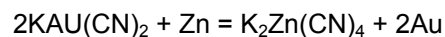
The gold precipitate is then filtered out of the solution, mixed with fluxes and smelted to form crude and impure bars which are sent to a refinery to remove the copper and silver, the process used depending on the impurities in the gold.

The major advantage of carbon-in-pulp recovery over Merrill Crowe recovery is the elimination of the leached ore solids and liquid separation unit operation. The separation step typically involves a series of expensive gravity separation thickeners or continuous filters arranged for countercurrent washing or filtration of the solids. For ores exhibiting slow settling or filtration rates, such as ores with high clay content, the countercurrent decantation (CCD) step can become cost prohibitive.

Ores with high silver content will generally suggest that Merrill-Crowe recovery be used. This is because of the very large carbon stripping and electrowinning systems required for processing large quantities of silver. The typical rule of thumb states that economic silver to gold ratios of greater than 4 to 1, will favor installation of a Merrill-Crowe system, but this decision can be altered if the ore exhibits very slow settling rates.

(iii) Electrowinning

Electrowinning, also called **electroextraction**, is the electrodeposition of metals from their ores that have been put in solution or liquefied [6]. **Electrorefining** uses a similar process to remove impurities from a metal. Both processes use electroplating on a large scale and are important techniques for the economical and straightforward purification of non-ferrous metals. The resulting metals are said to be *electrowon.*

In electrowinning, a current is passed from an inert anode through a liquid *leach* solution containing the metal so that the metal is extracted as it is deposited in an electroplating process onto the cathode. In electrorefining, the anodes consist of unrefined impure metal, and as the current passes through the acidic electrolyte the anodes are corroded into the solution so that the electroplating process deposits refined pure metal onto the cathodes.

(iv) Ion-Exchange/Solvent-Extraction

This is one of the emerging technologies which involve the recovery of precious metals from pregnant solutions by ion-exchange resins using the resin-in-column (RIC) technique [5]. The process is similar to CIC. One major exception involves the operation of the elution (stripping) stage which does not require elevated temperatures and pressures for removal of precious metals from loaded resins. Either strong or weak base resins may be used. Stripping of the loaded gold values from the resin has proven to be difficult and requires further research.

Solvent extraction of gold from alkaline cyanide solution was limited due to the lack of a selective extractant. Recent developments in solvent extraction using modified amines and alkyl phosphorus esters have been reported to provide for selective gold extraction from alkaline cyanide solution [5].

Patented Gold Extraction/Recovery Methods

Table 4 provides a summary of selected US patents related to gold extraction/recovery.

Table 4 Summary of selected US patents related to gold extraction/recovery

US Patent No.	Title	Date	Summary of Process
4,578,163	Gold recovery process	25/3/86	• Treatment of refractory ores • Pressure oxidation, cyanidation and CIP recovery • Flowsheet provided in Appendix A
4,597,791	Gold recovery processes	1/7/86	• Introduction of hydrophobic liquids such as grease and oil to achieve separation of gold from particulate matter
4,681,628	Gold recovery processes	21/7/86	• Technique for recovery of gold from alkaline aqueous liquid solution containing Au-CN ion and possibly Ag and/or Cu and/or Hg • Addition of thiourea to solution to allow formation of gold complex which is soluble and stable in dilute acid solution, Ag and Cu remains as precipitate and are separated
20080078269	Method of leaching gold	3/4/08	• Method for leaching Au from Cu sulfide ore. • Sulfide ores first subjected to leaching of Cu, producing leach residue having < 7.9% Cu • Leach residue mixed with solution containing chloride ion and ferric ion with pH 1.9 or less • Leaching reaction enhanced by the co-presence of either copper or bromide ions or both together with

			chloride and ferric ion.
7,498,006	Process for extracting gold in arsenic-containing concentrate of gold	3/3/09	• Extraction of gold from arsenic gold ore concentrate • Increase temperature of smelting chamber to 100-300°C, hold temperature to remove vapor and small quantity of dust • Under residual pressure ≤ 50MPa, increase temperature to 300-500°C to remove volatile arsenic sulfides • Hold temperature of crystalline chamber at 300-500°C, increase temperature of smelting chamber to 500-600°C to remove elemental sulfur • Increase temperature of smelting chamber to 600-760°C, lower temperature of crystalline chamber to 270-370°C to allow arsenic vapor to crystallize and obtain elemental arsenic • Lower temperature to obtain gold rich slag after dearsenization • Gold slag processed using conventional methods • Flowsheet provided in Appendix B

Mathematical Modeling of Gold Processes

Despite 100 over years of research and development with activated carbon, there is still not a complete understanding of the gold adsorption and desorption mechanism [5]. Majority of the modeling work carried out for gold processing are empirical in nature [7,8]. Limited studies on CFD modeling of extraction and recovery processes have been carried out on other mineral ores [9,10].

Modeling of heap leaching of gold by cyanidation

A mathematical model for heap leaching of gold ores by cyanidation was developed by Sanchez-Chacon and Lapidus in 1997 which describes gold heap leaching as a function of the mass transport steps involved, employing a rigorous kinetic expression to describe gold cyanidation [7].The model incorporates the results of investigation on trickle bed reactors, which consider the wetting efficiency of the mineral particles in the bed as a function of the Reynolds number of the leaching solution as it flows through the bed. From this parameter an apparent effective diffusivity of the species in the partially wetted particles is calculated. The numerical solution of the model equations allows the description of the reactant and product concentration profiles in the heap. From these profiles, mass balances are performed which show how the gold reacts and is transported until it finally leaves the heap.

The effect of different process and mineral variables, such as the mineral porosity, particle radius, leaching solution flow rate, gold grain size, the concentration of reagents and the heap height, on the gold extraction rate were also evaluated. The results obtained show that the controlling phenomenon in the gold extraction rate is the diffusion of the gold cyanide complex out of the mineral particles. Parameters such as the particle radius and porosity and the solution flow rate are important in determining the extraction rate. The study of the gold distribution in each step of the process as a function of time, calculated from the mass balances, would allow the implementation of dynamic operating policies in aspects such as variable feed concentration of reagents to reduce heap rinsing before closure.

Study of Merrill-Crowe processing

Based on the empirical model analysis, it was shown that the grade of the pregnant solution is the most significant parameter controlling zinc efficiency in Merrill-Crowe precipitation [8]. A flow sheet for Merrill-Crowe process is shown in Figure 3. An increase in the grade and flow rate of pregnant solution both increase zinc efficiency. An increase in NaCN concentration is detrimental to efficiency due to excessive dissolution of zinc.
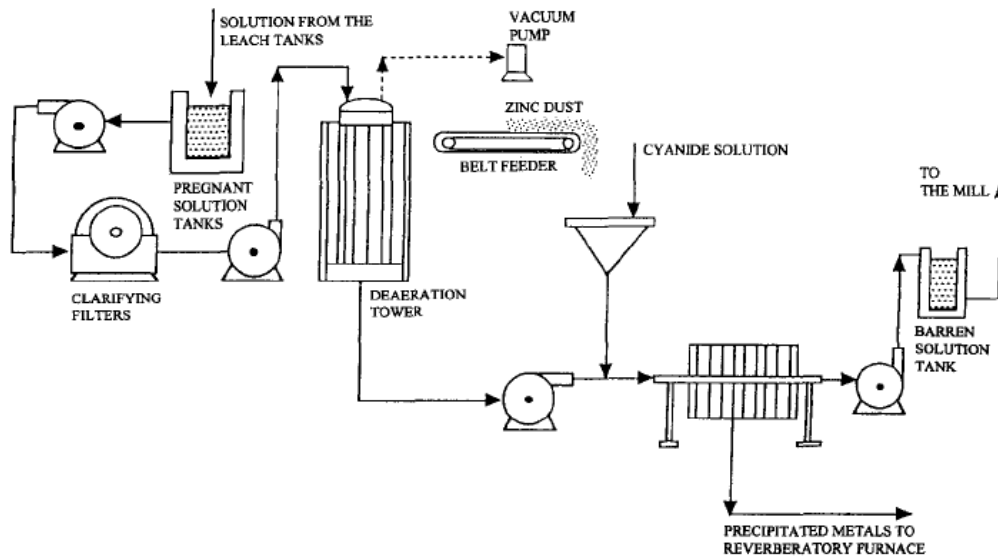
Figure 3 Flowsheet for gold and silver recovery by Merrill-Crowe Process [8].

CFD modeling and comparison with experimental residence time distributions in single and two phase porous flows

This paper focus on the CFD modeling and validation of flow of a non-reactive tracer through a porous medium in a column geometry to simulate the leaching of metals using heap-leaching methods [9]. The model is able to take into account the particle porosity and size distribution.

A two-dimensional CFD model for heap bioleaching of chalcocite

CFD model for heap bioleaching of chalcocite was developed to investigate the effect of poor oxygenation (in 2D) in heap bioleaching of copper sulfide [10]. Based on the results, it was found that under limited oxygen, the heap is leached from the bottom up progressively, as the oxygen became available to the upper regions, after the bottom regions have been leached as shown in Figures 4 to 6.
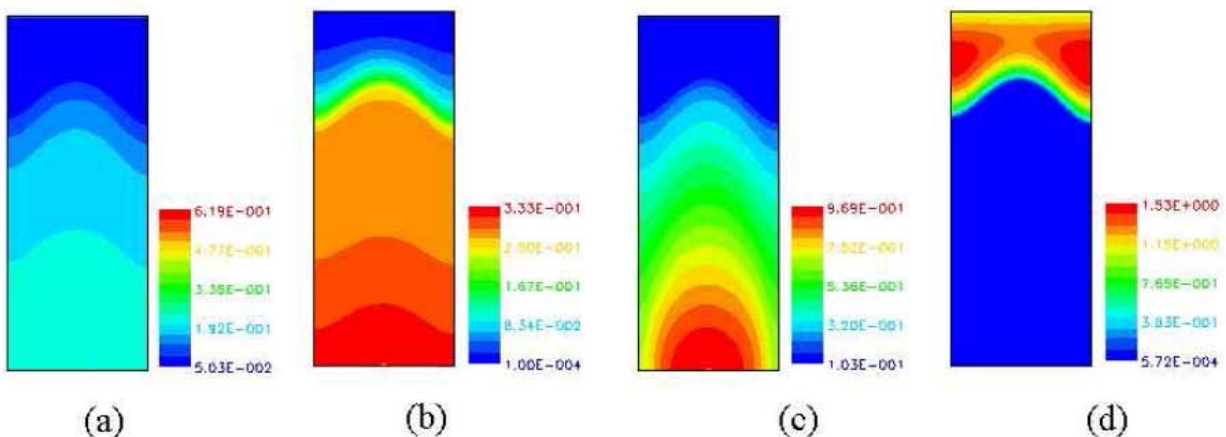

Figure 4 (a) Copper extracted α (b) bacterial concentration in solution (normalized by initial concentration $C_o = 10^{14}$ bacteria m^{-3} solution) (c) oxygen in liquid (normalized by initial oxygen concentration), and (d) ferrous ions (gL^{-1}), at 23 days.
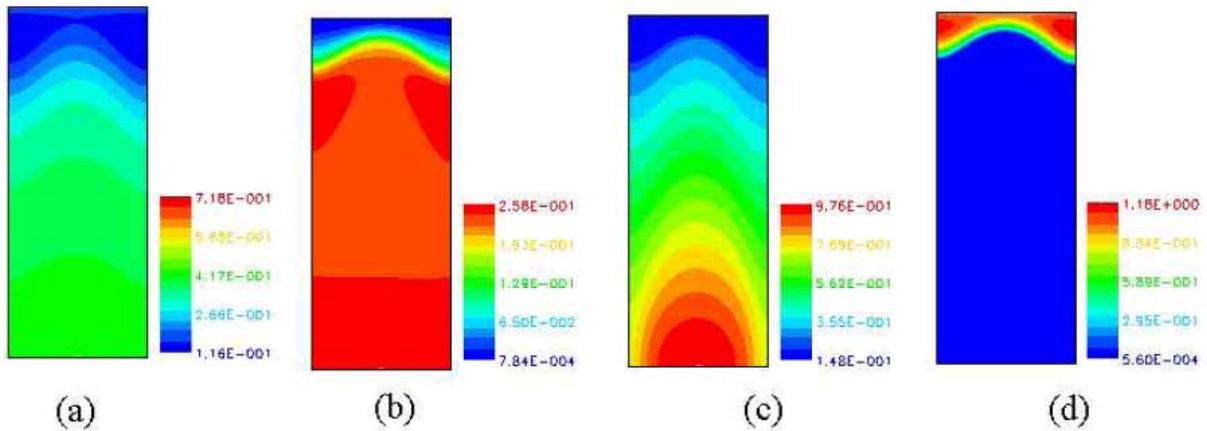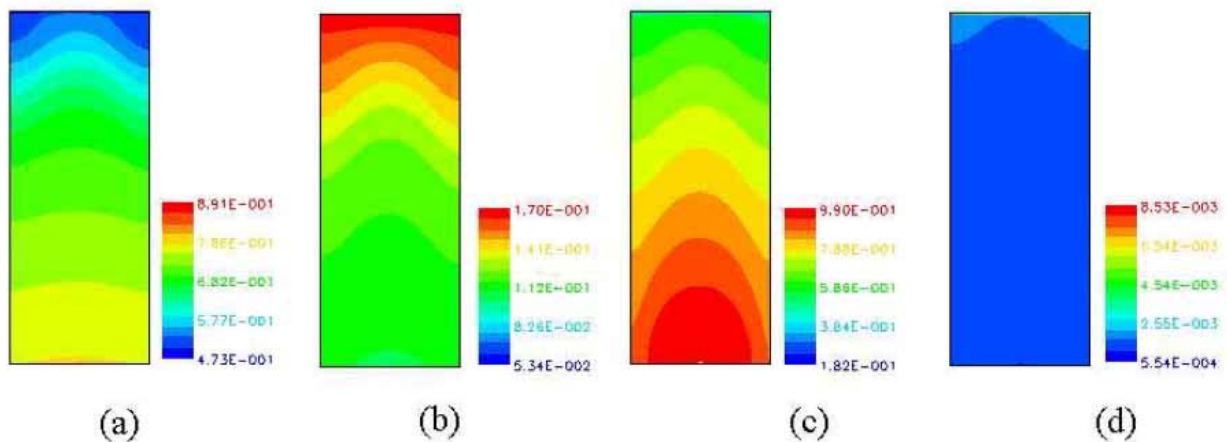
Figure 5 (a) Copper extracted α (b) bacterial concentration in solution (normalized by initial concentration $C_o = 10^{14}$ bacteria m^{-3} solution) (c) oxygen in liquid (normalized by initial oxygen concentration), and (d) ferrous ions (gL^{-1}), at 46 days.

Figure 6 (a) Copper extracted α (b) bacterial concentration in solution (normalized by initial concentration $C_o = 10^{14}$ bacteria m^{-3} solution) (c) oxygen in liquid (normalized by initial oxygen concentration), and (d) ferrous ions (gL^{-1}), at 116 days.

Possible Research Areas for M3TC

- Mathematical modeling of different gold leaching and recovery process
- Modeling of kinetics of gold leaching
- …………..

Examples of Commercial Mining & Recovery of Gold [11]

Case Study 1: Newmont Mining Corporation

1. Mining
To define the ore from the waste rock, samples are taken at set intervals along surveyed lines within the pit. These samples are assayed. Assay results are used to mark out areas of ore and waste rock, which are mined separately. Some of the harder areas require blasting to loosen the rock prior to excavation by hydraulic diggers. Dump trucks haul the rock to the primary crushers.

2. Crushing
The primary crushers - two Stamlers and a jaw crusher - located at the mine site, receive ore and waste at separate times. They break the larger rocks down to a size suitable for transport on the conveyor.

3. Transport
A rubber belted conveyor transports the ore and waste rock to the mill and waste disposal area. Large electromagnets remove any steel debris excavated from the old workings.

4. Grinding and Sizing
Ore is stockpiled at the mill before being fed into a semiautogenous grinding (SAG) mill with lime, water and steel balls. The larger particles from this mill are returned to the SAG mill for more grinding. The finer particles receive more grinding in a ball mill, and are size classified to give a final product of 80% <70 microns.

5. Leaching & Adsorption
A slurry of ground ore, water and a weak cyanide solution is fed into large steel leach tanks where the gold and silver are dissolved. Following this leaching process the slurry passes through six adsorption tanks containing carbon granules which adsorb the gold and silver. This process removes 93% of the gold and 70% of the silver.

6. Elution & Electrowinning
The loaded carbon is fed into an elution column where the bullion is washed off. The barren carbon is recycled. The wash solution—pregnant electrolyte—is passed through electrowinning cells where gold & silver is won onto stainless steel cathodes.

7. Bullion Production
The loaded cathodes are rinsed to yield a gold and silver bearing sludge which is dried, mixed with fluxes and put into the furnace. After several hours the molten material is poured into a cascade of moulds producing bars of doré bullion.

8. Water Treatment
Some water from dewatering the mine, from the embankment underdrains and decantation from the tailings pond is recycled for use in the grinding circuit. Excess water is pumped to the Water Treatment Plant and treated to the required standards before discharge into the river.

9. Tailings Disposal
Waste rock from the mine is used to build the embankment structures. The embankment retains the tailings slurry in a pond where solids settle and
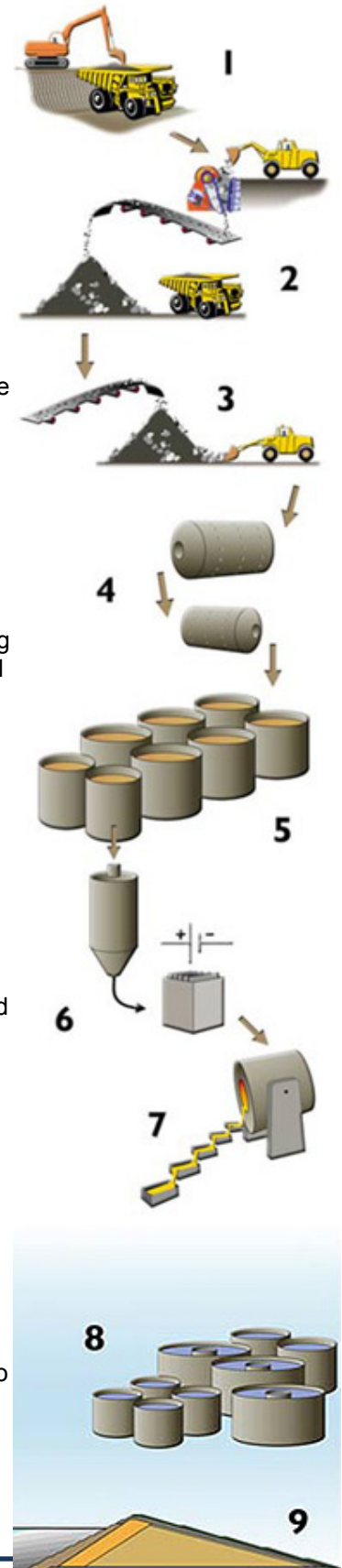
Figure 3 Schematic flowchart

compact. Water is decanted off and used in the process plant or treated before it is discharged.

Case Study 2: Jerritt Canyon, Yukon-Nevada Gold Corp

The mineral processing operation at Jerritt Canyon is very complex and is one of only three processing plants in Nevada that uses roasting in its treatment of refractory ores. Initially, Jerritt Canyon was designed to process oxide and mildly refractory gold ores by conventional cyanidation using chlorine gas for pre-oxidation of the refractory ores. In 1989, the roasting circuit was added to the process for the treatment of highly refractory ores which are now being mined and processed at Jerritt Canyon.

The unit operations at the Jerritt Canyon processing plant are comprised of the following circuits:

• Primary crushing;
• Secondary crushing;
• Fine ore drying;
• Tertiary crushing;
• Dry grinding;
• Roasting;
• Carbon-in-leach ("CIL") with cyanidation and carbon adsorption;
• Carbon stripping;
• Carbon reactivation;
• Merrill-Crowe process using zinc cementation of gold and silver;
• Precipitate refining;
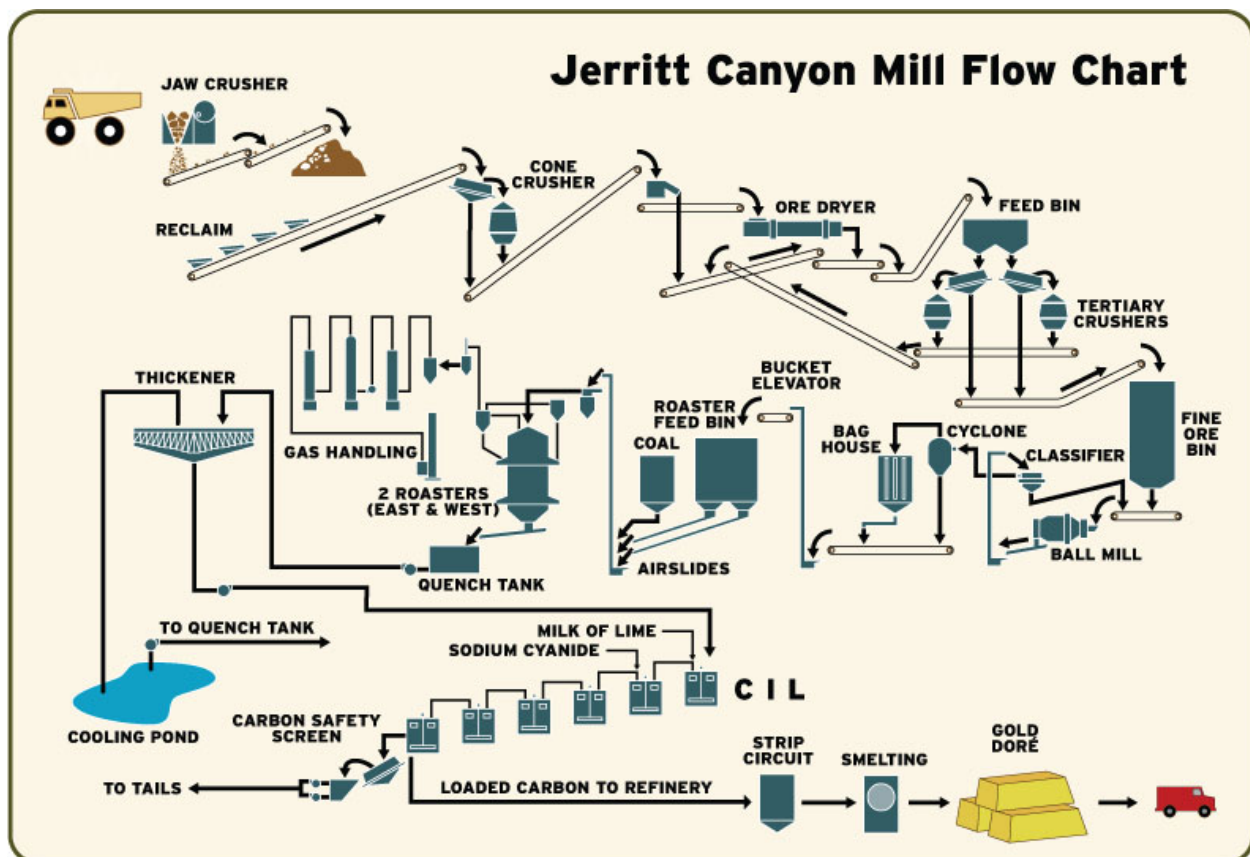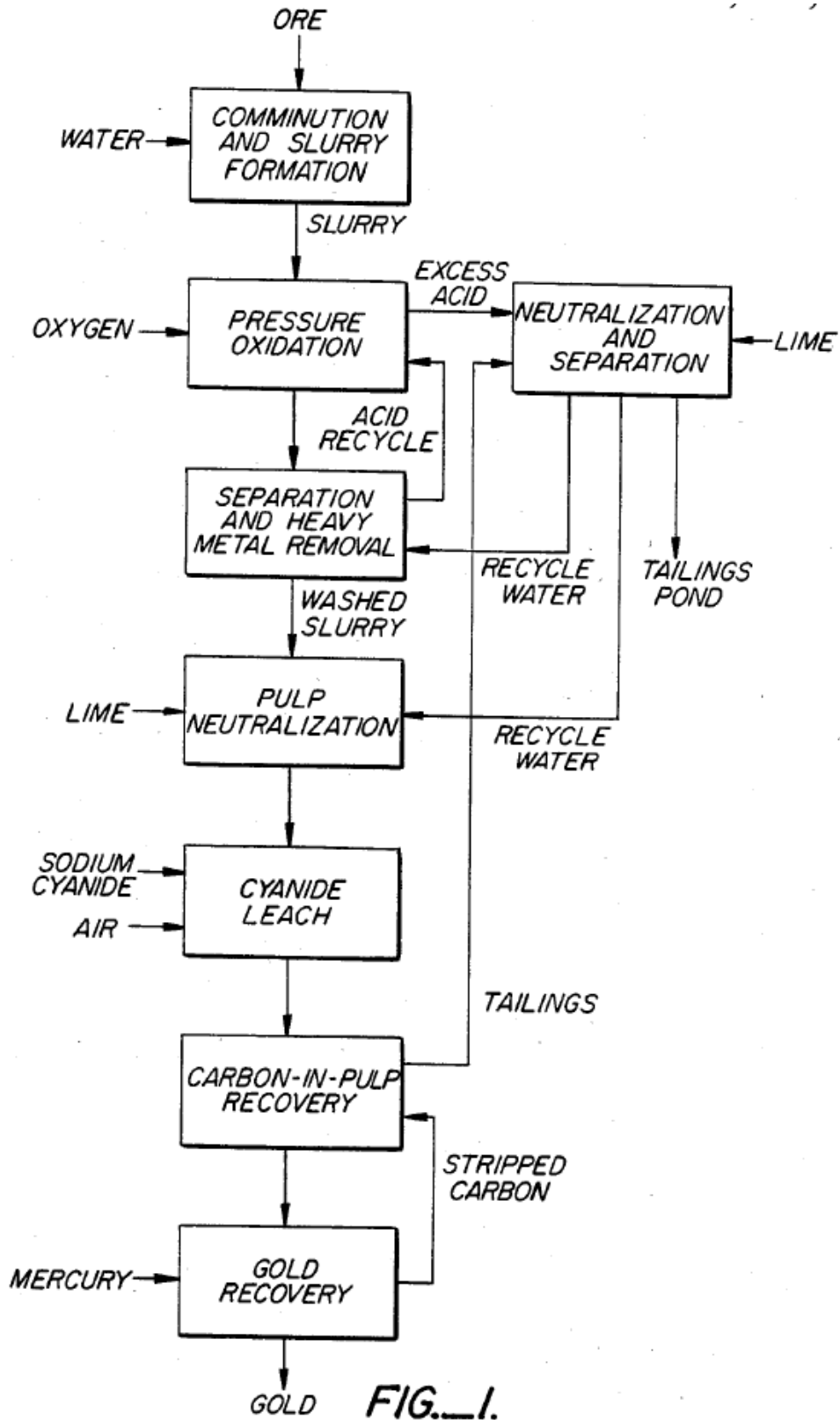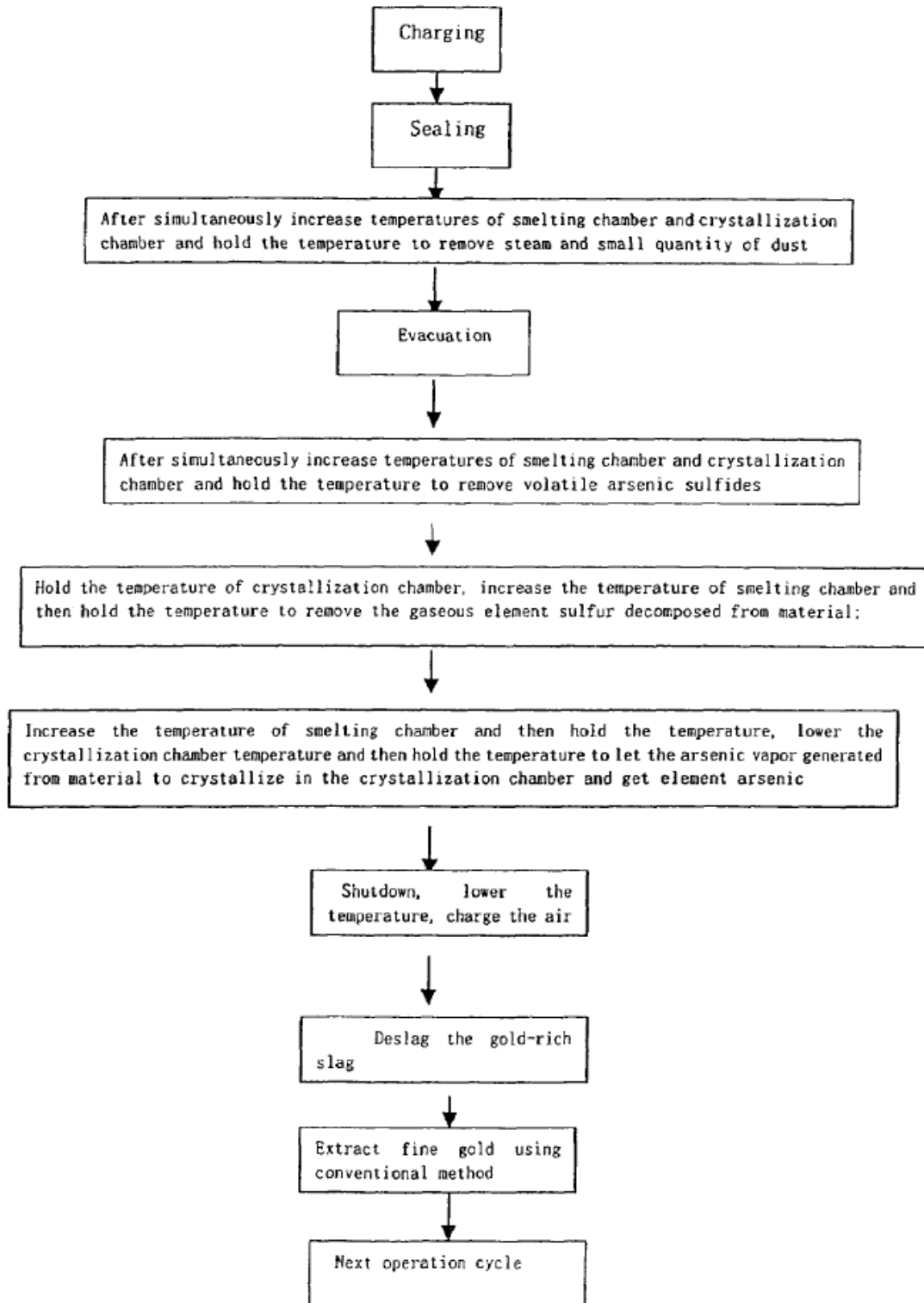• Oxygen plant; and
• Tailing impoundment.

Figure 4 Simplified flow chart of mineral processing operation at Jerritt Canyon.

Appendix A

FIG.—1.

Flowsheet for US Patent 4,578,163 Gold Recovery Process.

Appendix B

Flowsheet for US Patent 7,498,006B2 Process for extracting gold in arsenic-containing concentrate of gold.

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