The development of a jet reactor for the leaching of valuable metals

by B.M. Loftus, L. Lorenzen, and K.R.P. Petersen*

Synopsis

An investigation into the use of impinging stream (jet) reactors for the leaching of a free milling ore produced an increase in gold recovery by 10% while decreasing leaching time by up to 90%. Tests on refractory ores demonstrate no apparent improvement in recovery. However, leaching kinetics are dramatically increased when these ores are subjected to jet reaction prior to agitation.

Introduction

Impinging streams, a unique and multipurpose flow configuration of a two-phase suspension, first used in the 1960s, provide a simple tool for enhancement of transfer processes in heterogeneous systems. The applications are numerous, some of which are drying of solid particles, solid-solid and gas-gas mixing, absorption and desorption of gases from liquids in the presence and in the absence of a chemical reaction, combustion of gas and of coal, enrichment of phosphate ores, preparation of emulsions, liquid-liquid extraction, dissolution of solids in water and electrolytic processes[1].

In view of this diversity, it is hardly surprising that such technology would find its way into the minerals industry. The use of waterjet technology in mining and metallurgical industries has thus far been limited to abrasive waterjet drilling[2], granite cutting with abrasive waterjets[3], waterjet assisted excavation tools in coal mining[4] and granite quarrying[5]. One of the major challenges in the gold industry lies in the treatment of refractory ores, i.e. ores which are not readily treated by simple cyanidation. Previous methods developed for these ores include the roasting of sulphidic ores, chlorination of carbonaceous ores, pressure oxidation of sulphidic, pyritic and arsenopyritic ores, and bacterial oxidation of sulphidic ores. The use of lixiviants other than cyanide have also been investigated, but cyanidation still proves to be the most practical option. The use of intensive cyanidation methods, either by increasing pressure, temperature, cyanide concentration or oxygen concentration, are seldom advantageous.

In this investigation the properties of high velocity jet streams are used to assist in both the chemical and physical processes involved in the extraction of a valuable mineral, namely gold. By bringing gold bearing ore into contact with a high velocity jet of cyanide prior to mechanical agitation, gold recovery is increased and leach time dramatically reduced. The expected benefits arising from the use of jet reactors in leaching are energy savings, smaller leach tank requirements, high throughput and greater profitability due to increased gold production per unit of ore processed.

Treatment of refractory ores

Ores are termed refractory when direct treatment by cyanidation gives unacceptably low gold recoveries or is uneconomic for the following reasons[6]:

- gold is locked in gangue minerals, often sulphides, and cannot adequately be liberated, even by fine grinding
- gold occurs with minerals that consume unacceptable quantities of reagents, e.g. pyrrhotite, arsenopyrite
- gold occurs with carbonaceous materials which adsorb gold during leaching
- any combination of the above.

In the case of sulphidic ores, oxidation may be necessary to dissolve some, or all of the sulphide components in order to expose gold values and/or to passivate their surfaces, thereby preventing excessive consumption of reagents. The current means of scavenging gold sulphide concentrates from tailings at

* *Department of Chemical Engineering, University of Stellenbosch, Private Bag X1, Matieland, 7602, Stellenbosch.*

conventional gold plants is by flotation and subsequent roasting of the sulphides. The flotation concentrate is normally produced at a grade of 30% sulphur so that it is amenable to roasting. The sulphur is mostly present as pyrite (FeS_2) although there is also some present pyrrhotite and several base metal sulphides. Calcination, one of the most popular roasting processes by which gold is recovered from refractory sulphides only renders about 60% of the refractory gold amenable to subsequent cyanidation.

Other techniques developed for the treatment of sulphidic refractory gold ores include pressure oxidation and bacterial oxidation. Throughout the 1970s and 1980s Gencor (South Africa) worked on the development of bacterial oxidation for sulphidic refractory gold ores and in 1986 a 10 ton/day plant was commissioned at Fairview (South Africa) to treat flotation concentrates and has since been operating successfully. The continued interest in bio-oxidation processes is due to the potential cost savings over pressure oxidation and the considerable environmental advantages compared to roasting[6].

Carbonaceous ores contain organic carbon (> 1%), which has a strong gold-absorbing tendency and severely reduces gold extractions of over 80% to less than 80% during leaching. The carbonaceous constituents in these ores must either be passivated by chlorine or destroyed by roasting to enable gold extraction by cyanide leaching.

Jet reactor setup

The experimental set-up is shown in Figure 1. The cyanide solution is made up to be equivalent to 1kg of KCN per ton of ore and is contained in a storage vessel. The cyanide solution is pumped to the reactor by way of a high pressure reciprocal pump. Typical pressures produced vary between 200 and 300 bar. The ore slurry is contained in a stainless steel mixing drum and is pumped to the reactor by way of a slurry pump. Typical flow rates for the cyanide solution and the slurry are 1.5-2.0 l/min and 12-15 l/min respectively. The cyanided pulp exits from the reactor and is then agitated in a plastic holding drum, from which samples are taken.

The compact stainless steel reactor cavity is designed in such a way that contact between ore particles and cyanide is maximised and a milling action within the reactor is induced. A cross-flow of two ore slurry streams is introduced perpendicularly to a high velocity cyanide jet for intensive leaching action to take place. The high velocity cyanide jet is produced using a high pressure pump and passing the solution through an appropriate nozzle. The velocity and volumetric flow rate of the cyanide jet can be varied by regulating the pressure produced by the pump or varying the nozzle diameter.

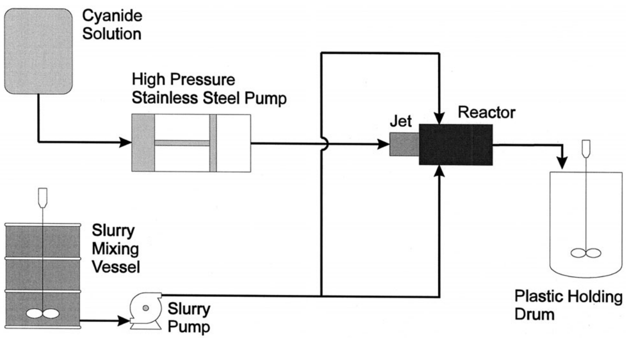

Figure 1—Schematic diagram of experimental set-up. A single cyanide stream and two slurry streams impinge to create a highly turbulent flow.

Experimental results

Physical parameters

In initial experiments, a free milling ore (President Brand) was used to determine optimum operating conditions. All the results are compared to the leaching result obtained by leaching the ore in an agitated vessel (kinetic run). A typical leaching result obtained from the jet reaction is shown in Figure 2 where it is clearly visible that gold recovery increases and leach time is reduced when the ore is first subjected to a jet of cyanide prior to agitation in the holding tank. In both experiments 1 kg/t NaCN, a pH value of 10 and 40% solids were the standard leaching conditions.

Flat spray tungsten carbide tipped nozzles were selected to produce the cyanide jet. Optimum operating conditions were determined by varying pressure, nozzle diameter and spray-angle. The relevant increases in recovery compared to that of a kinetic run are shown in Tables I to III.

An increase in cyanide pressure results in an increase in gold recovery. This can be attributed to the increase in both

Table I
Effect of cyanide jet pressure on recovery

Pressure, P (MPa)	Flow rate, Q (l/min)	Velocity, V (m/s)	Recovery (% increase)
10	0.83	161	2%
20	1.17	227	18%
30	1.46	284	20%

Table II
Effect of nozzle diameter on recovery

Diameter, ϕ (in. x 10^{-3})	Flow rate, Q (l/min)	Velocity, V (m/s)	Recovery (% increase)
13	1.17	227	18%
18	1.42	145	8%
31	6.11	209	7%

Table III
Effect of spray angle on recovery (large spray angles cause much of the spray energy to be dissipated into the reactor wall)

Spray angle, θ (degrees)	Flow rate, Q (l/min)	Velocity, V (m/s)	Recovery (% increase)
25°	1.56	158	3%
40°	1.42	145	8%
110°	1.45	147	1%

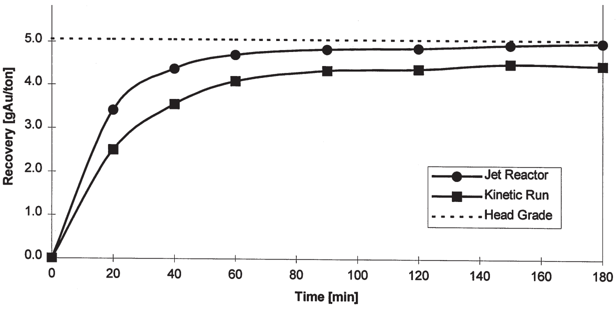

Figure 2—Typical graph of recovery versus time (the inclusion of the jet reactor shows a 10% improvement in the final amount of gold recovered)

the flow rate and velocity of the cyanide jet. The results obtained for a set of experiments where the nozzle diameter and spray angle are kept constant, while pressure is varied, are shown in Table I. There is a substantial increase in recovery from 2% to 18% for 10 and 20 MPa respectively.

The small increase in recovery at 30 MPa can be ascribed to the high viscous pressure forces encountered in the nozzle which negates any further major increase in flow rate $(Q \propto \sqrt{P})$ and eventually leads to a physical degradation of the nozzle. It is likely that the increase in flow rate from 1.17 to 1.46 l/min for a pressure change from 20 to 30 MPa is partly due to nozzle failure.

The results obtained for a set of experiments where pressure and spray angle are kept constant, while nozzle diameter is varied, are shown in Table II. As the diameter increases, the flow rate increases, while velocity decreases. An increase in recovery with a decrease in nozzle diameter is noted. This indicates that jet velocity (a result of flow rate and nozzle diameter) is pivotal to effective leaching. However, the effect of cyanide concentration needs to be evaluated, since lower cyanide concentrations were used at high flow rates through the reactor to maintain continuity in cyanide supply from the holding tank.

The effect that the spray angle has on recovery can be seen from Table III and Figure 3. Gold recovery is best for a spray angle of 40° where the jet cuts the entire face of the slurry entering the reactor. At a wider spray angle of 110° the energy of the cyanide jet is absorbed largely by the reactor walls.

Chemical and physical parameters

The effect that various chemical and physical parameters such as cyanide concentration, slurry flow rate, slurry density and pH may have on leaching kinetics was investigated. A free milling ore (President Brand) was used in these tests. Optimum physical operating parameters were selected based on the previous findings. The nozzle used throughout these experiments had a diameter of 0.018 inches and a spray angle of 40° (C1840). All experiments were conducted at 30 MPa. The results of the sensitivity analysis are summarized in Table IV. The kinetic run (in an agitated vessel) was done under the following conditions: KCN = 1 kg/t; pH = 10; and slurry density = 40% solids.

From Table IV it is evident that slurry flow rate and pH do not have any notable effect on the leaching kinetics for jet reaction. However, cyanide concentration and slurry density drastically affect leaching kinetics.

Leaching kinetics are sensitive to cyanide concentration. There is a large increase in the amount of gold leached for cyanide concentrations of 1.0 kg/t as compared with 0.2 kg/t. There is no increase in gold dissolution when the cyanide concentration is increased to 2.0 kg/t, since there is already an excess of cyanide at a concentration of 1.0 kg/t. Gold dissolution decreases sharply with an increase in slurry density. This is due to particle-interaction and the poorer contact with the cyanide associated with an increase in slurry density.

Refractory ore testing

Kinetic and jet reactor leaching tests were performed on various refractory ore types. The following ores were tested: (1) mixed run of the mill ore from Free State Geduld Mine (F.S.G.) (2) a pyritic flotation concentrate from Barberton and (3) calcine from President Brand Gold Mine. Although many of the results obtained were quantitatively inconclusive, the use of jet reaction with refractory ores may show promise.

All the ore types previously mentioned produced very similar results when subjected to jet reaction. A typical leaching result is shown in Figure 5. Results obtained show a

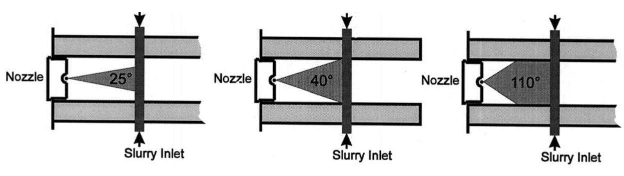

Figure 3—The effect of the spray angle (larger spray angles only serve to dissipate fluid energy into the reactor walls

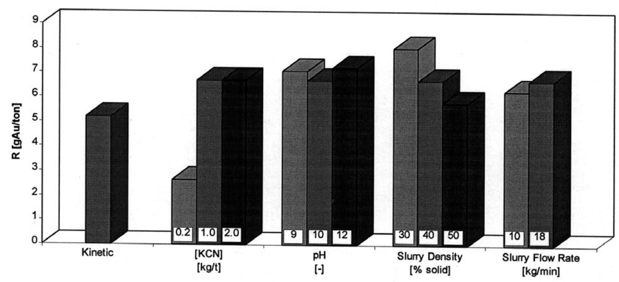

Figure 4—Sensitivity analysis done for a free milling ore. The effect of cyanide concentration, pH, slurry density and slurry flow rate are investigated

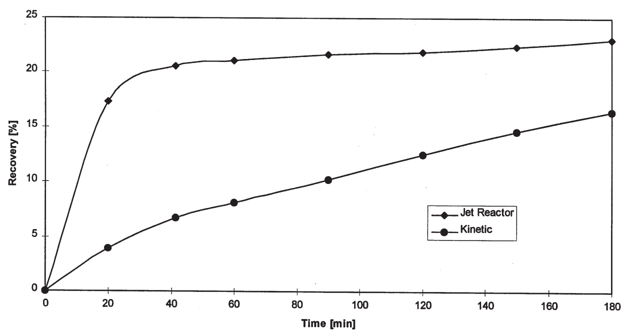

Figure 5—A typical leaching result obtained for refractory ores

definite increase in the leaching kinetics, which leads to a reduced leach time. However, increase in recovery is not evident over a 24-hour leaching time, and it appears that the same recovery will be obtained for the kinetic run after continued agitation. The complex mineralogy of these ores needs to be taken into consideration, that together with jet reaction, a process to overcome the leaching problems associated with these ores can be developed.

Discussion

A Scanning Electron Microscope (SEM) was used to obtain qualitative visual data of treated particles in order to determine if micro-cracking is realised (See Figure 6). SEM images obtained at a magnification of 12000X do not provide any substantial evidence that micro-cracking occurs as a result of impinging contact. However, these images do not discount the possible effects of attrition and size reduction which would lead to an increase in particle surface area amenable to leaching, and therefore an increase in recovery.

As in the case of micro-cracking, it is also not clear if any significant size reduction occurs other than through the abrasion process. Despite the relatively simple configuration of impinging streams, the related fluid flow characteristics are quite complex. Tamir[7] has shown that under certain conditions, the contact area between the impinging streams reduce through instabilities that cause the two streams to rotate around each other. Sitek *et al.*[8] point to the fact that the observed increased leaching kinetics are probably due to the intensive mixing rather than micro-cracking, since much higher jet velocities would be required for cracking to occur. Experiments in waterjet cutting show that particles disintegrate upon passing through a mixing chamber. However, in this investigation, pressures are limited to between 30 and 40 MPa, which would restrict comminution action to abrasion.

Other reasons for an increase in leaching kinetics could be attributed to the impinging stream reaction taking place within the reactor which reduces the external resistance to diffusion by :

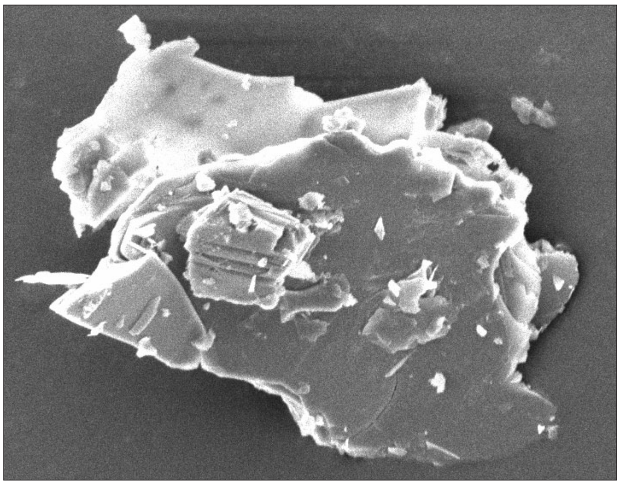

Figure 6—Single particle magnified 12000x. A small crack at the bottom of the particle gives little evidence that micro-cracking can be a contributor to increased recovery

- increasing the relative velocity between the particles and the continuous phase, which is also associated with an increase of the inter-phase friction
- reducing the dimensions of the particles, which promotes reduction of the laminar sub-layer thickness formed near the surface
- uniform distribution of the dispersed particles in the continuous phase and maintaining small distances between them, again promoting reduction of the laminar sub-layer and
- exerting additional effects on the particles, such as inertia or centrifugal forces, which might promote reduction in the thickness of the fluid layer near the solid surface.

Summary and conclusions

This paper investigates the application of jet reaction technology to the leaching of valuable minerals, in particular refractory gold. Two slurry streams and a single cyanide stream are impinged under high pressure (30 MPa) in order to improve the recovery kinetics (mass transfer) in gold leaching. Results show that recovery is improved by up to 10% for non-refractory ores. Little improvement in the case of the refractory ore indicates that micro-cracking may not be occurring, a fact which is supported in the literature[8]. Rather, increased mass transfer due to the relatively high pressures and particle abrasion (size reduction) are proposed as being the main reasons for improved recoveries. The advantages of jet leaching are related not only to the ability to improve recovery in some ores but also to decreasing cyanidation times by up to 90% in some cases.

Notation

P	pressure (bar)
Q	volumetric flow rate (l/min)
R	recovery
t	time (min)
V	velocity (m/s)

Greek Symbols

ϕ	diameter (inches)
θ	spray angle (degrees)

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