

Precious Metals 07



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BIOGENIC SULPHIDE FOR CYANIDE RECYCLE AND COPPER RECOVERY IN GOLD-COPPER ORE PROCESSING

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ABSTRACT

Many complex-ore gold deposits with cyanide-soluble copper minerals such as chalcocite, covellite, bornite, cuprite, malachite and azurite are now being considered for processing. In some cases the ore is not currently being mined largely due to the various issues associated with the cyanide-soluble copper minerals in the ore, resulting in low gold recoveries and high cyanide consumption and detoxification costs. Moreover, the presence of copper in tailings supernatant tends to stabilize weak-acid dissociable cyanide in a form toxic to wildlife.

In the SART process (sulphidization–acidification–recycle–thickening), the cyanide associated with the copper cyanide complexes is released by NaHS dosing to precipitate copper and convert cyanide to HCN gas under weakly acidic conditions, allowing it to be recycled back to the leach process as free cyanide. Copper is also recovered as a valuable, high-grade (~70% Cu) Cu₂S by-product. Cyanide recycling allows the leach circuit to be operated at higher cyanide levels, maximizing leach efficiency and minimizing copper department to gold electrowinning. The first commercial plant is at Telfer in Western Australia.

Biogenically-produced hydrogen sulphide can be used to replace chemical sulphide at significantly lower cost and with the added advantage of lowering the acid demand substantially. While the capital cost of a biogenic SART plant will be higher than a cyanide detoxification plant, this will be more

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than offset by the revenues generated by copper recovery and the savings realized by cyanide recycle, allowing for a short payback time on the incremental capital.

BioteQ is currently working with Columbia Metals Corporation Ltd., Canada, to apply its sulphide generating and precipitation technology in a SART circuit at both of Columbia's gold projects (La Jojoba and Lluvia de Oro) in northern Mexico. Processing of ores from both mines has presented challenges resulting from the presence of cyanide-soluble copper. This paper reviews the BioteQ biogenic SART process technology, economics and commercial status as well as environmental and operating outcomes.

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Keywords: Gold ores; Tailings disposal; Cyanidation; Biotechnology; Recycling

INTRODUCTION

As more complex gold orebodies become exploitation targets, an increasing number of gold deposits with cyanide-soluble copper minerals such as chalcocite, covellite, bornite, cuprite, malachite and azurite are being considered for processing. In many of these cases the ore is not currently being mined, largely owing to the metallurgical challenges, high costs and environmental issues associated with the cyanide-soluble copper minerals in the ore (Sceresini, 2005). Leachable copper can result in low gold recoveries as well as high cyanide consumption and consequent destruction costs. Moreover, the presence of copper in tailings supernatant tends to stabilize weak-acid dissociable cyanide in a form toxic to wildlife yet less amenable to natural degradation processes (Adams, 1999).

In concert with these trends is the increasing focus on sound environmental stewardship in mining operations, particularly pertaining to responsible cyanide use. The world's major mining companies have already signed their commitment to the International Cyanide Code, which currently prescribes a maximum weak-acid dissociable (WAD) cyanide level not exceeding 50 mg/L at tailings storage facility (TSF) spigot, amongst other requirements (reviewed recently by Gibbons, 2005). For this reason gold mining companies are considering their options for the destruction or recovery of tailings cyanide to meet this target.

This paper will discuss a new application of BioteQ's BioSulphide[®] technology involving biogenic sulphide generation and its techno-economically effective use in the treatment of copper cyanide solutions for copper recovery and cyanide regeneration.

GOLD-COPPER ORE PROCESSING

The processing of ores containing both gold and copper presents a variety of challenges to the operator, dependant upon the relative grades. Processing of gold-copper ores (higher gold values than copper values), which is the focus of this paper, typically follows the simple route of whole-ore cyanidation with recovery by carbon-in-pulp (CIP) or carbon-in-leach (CIL) or conventional heap leaching that employs carbon for gold recovery from the pregnant solution. Copper-gold ore processing (higher copper values than gold values) generally involves flotation and smelting. In the latter case, gold credits are obtained from the smelting of the copper concentrate, and if gold reports to the flotation tailings, they may also require cyanidation. A notable and relevant exception to this generalization is that of Newcrest Mining's Telfer plant, where pyrite-locked gold is recovered by second-stage flotation (after chalcopyrite concentrate production for copper smelting) and the pyrite concentrate is subjected to intensive cyanidation. Cyanide and copper are recovered by conventional SART, which employs NaHS as the sulphide source, in the most recent commercial application of this process.

Copper is chiefly introduced in to gold cyanidation leach circuits when small amounts of cyanide-soluble copper minerals are present in the ore; hence an understanding of ore mineralogy is critical to improving process management in these cases.

Gold-Copper Ore Mineralogy

Deposits containing gold and copper are mainly associated with Proterozoic and Phamerozoic rocks, primarily in Australasia and South America, although there are isolated deposits scattered throughout the world, some with sub-economic 'nuisance' copper. Several large deposits have more recently been

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found in Indonesia (Carlisle and Mitchell, 1994), containing resources in excess of 2,500 tons of gold and 20 million tons of copper mineralized in porphyry, skarn and enargite.

Association of gold exclusively with copper minerals is rare, as there is often some pyrite and other sulphide minerals present. Gold is not usually encapsulated or submicroscopic in copper minerals, unlike its occurrence in pyrite and arsenopyrite. Major copper minerals are listed in Table 1, along with their cyanide leaching characteristics. Chalcopyrite (CuFeS_2) is the most abundant copper mineral. Chalcocite (Cu_2S) and covellite (CuS) are formed by the alteration of primary copper sulphide ores such as porphyries. Bornite (Cu_5FeS_4) is generally a minor component of copper-gold ores.

Gold-Copper Ore Processing

This topic has been thoroughly reviewed, most recently by Sceresini (1999); hence the focus here is on the main challenges presented by copper contamination of gold cyanidation circuits.

Table 1 Major Copper Minerals and Their Cyanide Leaching Characteristics (After Adams, 1999)

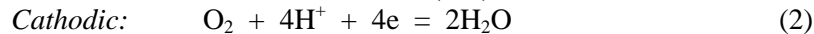
Mineral	Composition	Leaching rate in Cyanide
Oxide Minerals		
Azurite	$2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$	Fast
Malachite	$\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$	Fast
Cuprite	Cu_2O	Fast
Tenorite	CuO	Fast
Sulphide minerals		
Chalcocite	Cu_2S	Fast
Covellite	CuS	Fast
Chalcopyrite	CuFeS_2	Very slow
Cubanite	CuFe_2S_3	Slow
Bornite	$\text{FeS} \cdot 2\text{Cu}_2\text{S} \cdot \text{CuS}$	Moderate
Enargite	$3\text{CuS} \cdot \text{As}_2\text{S}_5$	Slow
Tetrahedrite	$4\text{Cu}_2\text{S} \cdot \text{Sb}_2\text{S}_3$	Slow
Other minerals		
Valeriite	$\text{Cu}_2\text{Fe}_4\text{S}_7$	Slow
Native copper	Cu	Fast
Chrysocolla	$\text{Cu}_2\text{SiO}_5(\text{OH})_5 \cdot n\text{H}_2\text{O}$	Slow

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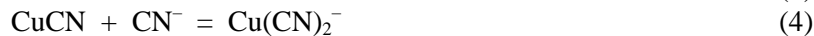
Leaching

The major challenges to the processing of gold-copper ores using cyanidation is that of the high cyanide consumptions that are typically experienced, along with effective control of the leach, particularly when there is variable cyanide-soluble copper in the ore.

The gold leaching reaction in cyanide solution follows the electrochemical half-reactions:



Cyanide also forms series of complexes with several metals, including copper:



The pH-potential diagram for the copper-cyanide-water system is illustrated in Fig. 1 (the area contained within the dotted lines corresponds to the region of stability of water). The $\text{Cu}(\text{CN})_3^{2-}$ complex is the most predominant under typical leach conditions of pH value around 10.5 with some excess free cyanide. Shown are conditions approximating those encountered in practice.

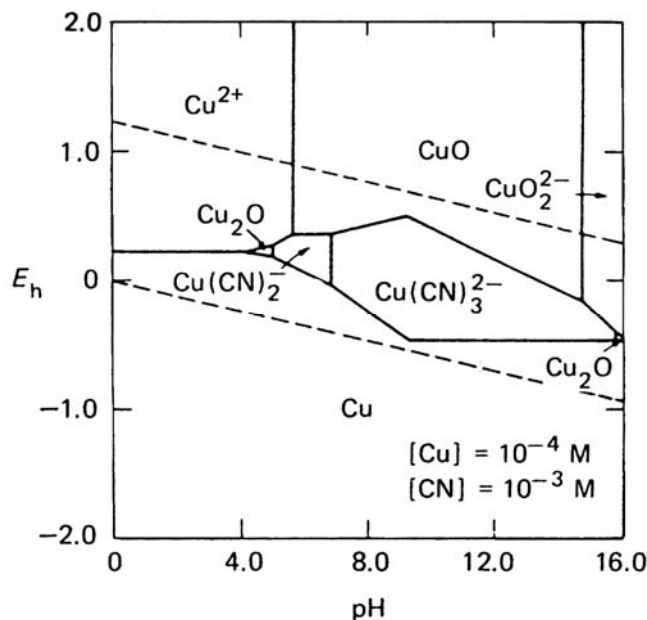


Fig. 1 pH-potential diagram for the copper-cyanide-water system (after Osseo-Asare, 1984)

The effect of free cyanide on the relative proportion of copper-cyanide complexes in typical tailings solutions is given in Fig. 2.

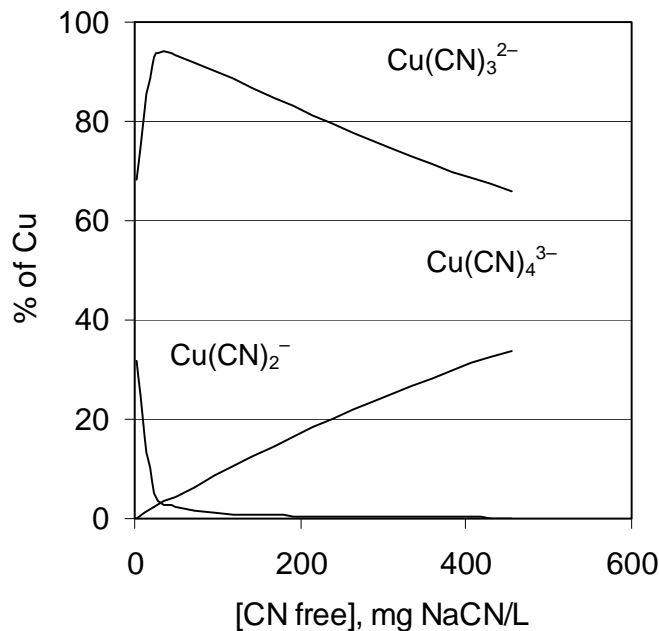


Fig. 2 Influence of free cyanide levels on copper-cyanide species at pH 10.5 and 40 mg/L Cu (after Adams, 2000)

Sufficient free cyanide must be present for effective gold leaching, and large amounts of cyanide-soluble copper can rapidly decrease the available cyanide far below the levels required, resulting in unleached gold losses in tailings solids or heap-leach residues. Moreover, there is evidence (Adams, et al., 1996) that under these cyanide-deficient conditions, soluble gold is adsorbed back on to copper minerals such as chalcopyrite and chalcocite, by reduction on to surface defect sites, again resulting in loss to tailings.

A general operating principle for the leach is to maintain a molar ratio of added CN:Cu of no less than 4, and preferably over 5. The use of cyanide autoanalyser or at minimum, more frequent cyanide titrations, is often required to achieve this. In cases where there is a large amount of cyanide-soluble copper, such as an intensive leach, copper levels of ~1,000 mg/L have been observed, requiring concomitantly high cyanide additions.

Adsorption of copper cyanide complexes on to activated carbon in the adsorption stage for gold recovery follows the trend:



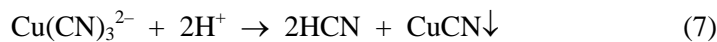
The predominance of the Cu(CN)_2^- complex under cyanide-deficient conditions is yet another reason to maintain excess free cyanide in the leach, to avoid significant copper loading, which may push gold off the carbon, elevating soluble gold losses. Moreover, excess copper in the eluate reduces electrowinning cell efficiency, resulting in copper-contaminated doré bullion.

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Measures such as selective mining are often not applicable, given that gold and copper mineralization is often concurrent in these ores. Chemical means of removing reactive copper, such as acid leaching, are generally not economic. Alternatives include the addition of ammonia to the cyanide leach to suppress copper leaching (Hunt, 1901; Muir, 1995; Drok and Ritchie, 2000); this option has only seen minor application (Butcher, 1995) and is reported to be difficult to control in practice. Copper mineral dissolution can be suppressed by means of surfactants such as fatty alkyl amines (Bennett *et al*, 1991), which passivate the copper mineral surfaces, thus reducing copper dissolution. There may also be a reduction in gold leaching, however.

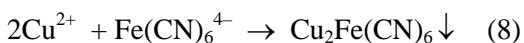
Tailings Detoxification

The leach operating strategy described above results in higher than average tailings cyanide levels when compared with low-copper leachates. Moreover, the $\text{Cu}(\text{CN})_3^{2-}$ complex, which predominates once the excess ionic cyanide levels have been lowered by HCN volatilization, is quite stable under typical tailings conditions (pH 7-10). However, on ingestion of tailings supernatant or runoff water by avian or mammalian wildlife, the acidic conditions in the stomach result in rapid release of free cyanide, and death:



Therefore, process plants that produce cyanide tailings from gold-copper ore processing typically need to incorporate some form of cyanide detoxification or recycling circuit, and this adds to both the capital and operating costs of the plant. The most common detoxification circuits involve some form of oxidation, such as the popular SO_2/Air process as well as the Caro's acid (H_2SO_5) process. Depending on the amount of copper and cyanide present in the tailings water, reagent costs for these processes can be prohibitive, and in these cases some form of cyanide recovery or recycling can be contemplated.

Copper reports to the tailings in the form of hydroxides, CuCN and via the precipitation of the highly insoluble $\text{Cu}_2\text{Fe}(\text{CN})_6$ compounds, provided iron is present:



This reaction occurs on the surface of copper minerals, and has been found to have an important role to play during cyanide detoxification using various processes (Adams and Kyle, 2000).

Cyanide Recovery Processes

Several ion-exchange resin-based processes (Goldblatt, 1956, 1959; Fleming *et al.*, 1995) and activated carbon-based processes (Adams, 1994) have been developed and tested over the past fifty years for the recovery of free or copper-bound cyanide from solution. While these processes may be proven useful for specific cases, they have yet to have enjoyed commercial application to gold plant tailings. Moreover, rapid saturation of the adsorbent is likely to become an issue where copper and cyanide levels are high, resulting in high adsorbent turnovers and inventories. Adsorbent-based processes may be economic in cases where solid-liquid separation costs or operability are an issue. It should be noted that tailings thickeners are often used in gold circuits.

The AVR (acidification-volatilization-regeneration) process involving the addition of acid to pH ~2.5 with stripping and subsequent recovery of HCN by scrubbing has seen some commercial application

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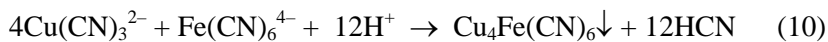
(Riveros, et al., 1993), most recently in the pH ~4-5 variant (Stephenson, et al., 1998). Copper is not recovered for resale in this process however. Moreover, copper that is precipitated in the form of CuCN may potentially be remobilized on contact with spikes of elevated cyanide during process upsets, for example.

The titratable cyanide component (commonly determined by silver-nitrate titration and approximated as the CN^- , HCN, zinc-bound cyanide and the fourth cyanide ligand from $\text{Cu}(\text{CN})_4^{3-}$) is easily recoverable by volatilization of the produced HCN (aq) at lowered pH value:



In the presence of copper, insoluble CuCN is produced via Reaction (7), resulting in the loss of the copper as well as substantial cyanide to tailings solids.

In the presence of both copper and iron, a mixed-metal insoluble compound is produced, via Equation (8) under aerated or oxidizing conditions, forming $\text{Cu}_2\text{Fe}(\text{CN})_6$, and via Equation (10) under reducing conditions, producing $\text{Cu}_4\text{Fe}(\text{CN})_6$:

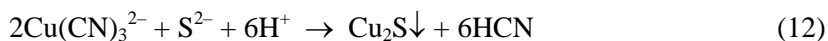


In these cases, not only is the copper lost to tailings, but also six moles of cyanide for every mole of iron present in the leachate.

When thiocyanate is present, as is often the case when leaching reactive sulphide-bearing ores or bacterial oxidation residues, for example, insoluble CuSCN may also be responsible for copper precipitation in the AVR process at pH ~2 after cyanide levels have dropped (CuSCN solubility product $K_{\text{sp}} = 1.8 \times 10^{-13}$; lower than that of CuCN $K_{\text{sp}} = 3.0 \times 10^{-20}$):



Addition of sulphide ions to the acidified cyanide solution results in the precipitation of cuprous sulphide (synthetic chalcocite), which is favoured because of its extremely low solubility ($K_{\text{sp}} = 2.3 \times 10^{-48}$):



This reaction is irreversible at pH values below four and takes place quantitatively with stoichiometric additions of sulphide ions and acid. Equation 12 forms the chemical basis of both the SART process (MacPhail, et al., 1998), which is described in more detail below, and the similar MNR process (Potter, et al., 1986). The optimum pH for liberation of cyanide from tailings solution by sulphide dosing will be case-specific and dependent on the cyanide speciation in solution.

BIOSULPHIDE® COMMERCIAL APPLICATION

BioSulphide® Process Flowsheets

Sulphide reagents are widely used in mineral processing, hydrometallurgical operations and water treatment. The precipitation of metals using sulphide is fast, efficient and can produce barren solutions

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and effluents with very low concentrations of residual metals. BioteQ's BioSulphide[®] technology for the generation of biogenic sulphide reagent by reduction of elemental sulphur at a lower cost than the chemical sulphide reagents has been described elsewhere (Lawrence, et al., 2005; Lawrence, et al., 2007). In some smaller BioteQ plants, currently operating or under construction, NaHS is used for selective metal precipitation and recovery in a process known as ChemSulphide[®].

A typical flowsheet utilizing the biogenic generation of sulphide reagent as hydrogen sulphide to precipitate selectively metals contained in the feed water is shown in Fig. 3.

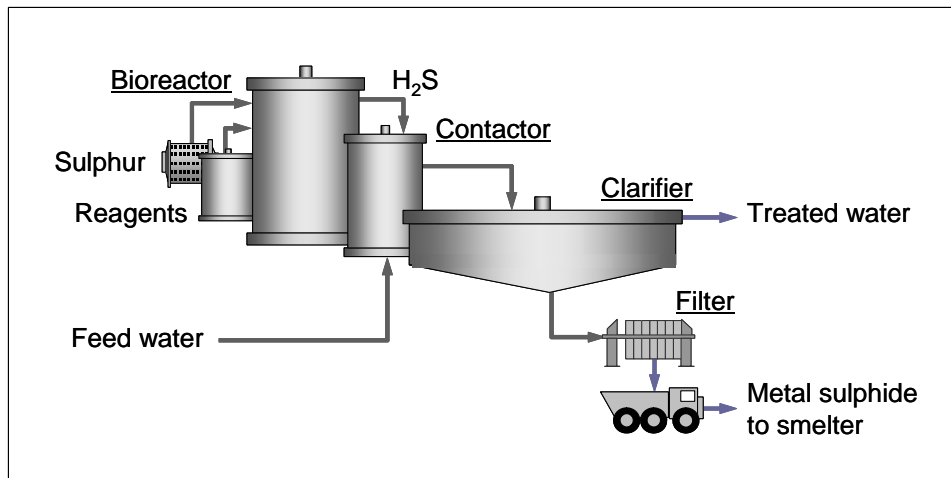


Fig. 3 Simple flowsheet schematic of the BioSulphide[®] Process

Hydrogen sulphide is generated by the reduction of elemental sulphur, or other sulphur source, in the presence of an electron donor such as acetic acid in an anaerobic bioreactor. The gas is passed to an anaerobic agitated contactor where conditions are controlled to selectively precipitate the metal to be recovered as a sulphide. The high-grade metal sulphide precipitate is then recovered by conventional clarification and filtration to produce a filter cake which can be shipped to a smelter. The feed water does not pass through the bioreactor, which can be operated under ideal conditions at all times. The operation of the bioreactor is not subject to process upsets due to changes in water chemistry and flow, unlike other biological processes which act directly on the water to be treated.

The main advantages of using the biological H₂S generation include:

- Low cost of sulphide compared to the cost of Na₂S, NaHS, or H₂S;
- Minimal hazards and increased safety mainly due to the low system pressure and low inventory of H₂S, avoiding the need for special environmental permitting and personnel for sulphide reagent storage;
- Low capital cost mainly due to the ambient temperature and pressure in bioreactors that are designed as conventional stirred tanks compared to pressure vessels with expensive agitator seals; and
- Easy to scale-up and down over a wide range of H₂S production capacities.

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If more than one metal is to be recovered, a single bioreactor can provide sulphide reagent to separate contactor-dewatering circuits. It is possible, for example, to produce separate and high grade sulphide concentrates of Cu, Zn, Ni-Co and Mn.

BioSulphide® Process Plants and Projects

Since 2001, BioteQ has constructed and operated three commercial operations utilizing sulphide generation and precipitation technology (upstream of a lime plant at the Caribou Mine in New Brunswick for zinc-lead-copper-cadmium; copper recovery from stockpile drainage at the Copper Queen Mine in Bisbee, Arizona; and treatment of nickel-containing mine drainage at the Raglan Mine, in northern Quebec). Four new plants are currently under construction in 2007, with a further four in the design phase for planned construction in 2008.

BioteQ's first copper recovery plant was constructed and is operated in joint venture with Phelps Dodge at the Copper Queen Mine, in Bisbee, Arizona. The success of the plant has opened up numerous opportunities to use biogenic sulphide for the recovery of metals including copper, nickel, zinc and cobalt at a number of sites around the world. The recovery of copper at Bisbee has demonstrated that the technology has a niche for profitable operation for the treatment of solutions too low grade for economic application of solvent extraction – electrowinning (SX-EW) and with a significant lower capital investment.

The Bisbee plant was commissioned in 2004 and was designed to recover up to 3 million pounds (1,360 tonnes) per year of copper from the drainage of a large low-grade stockpile with flows of up to 10,900 m³ per day. Fig. 4 shows a simplified flowsheet of the operation.

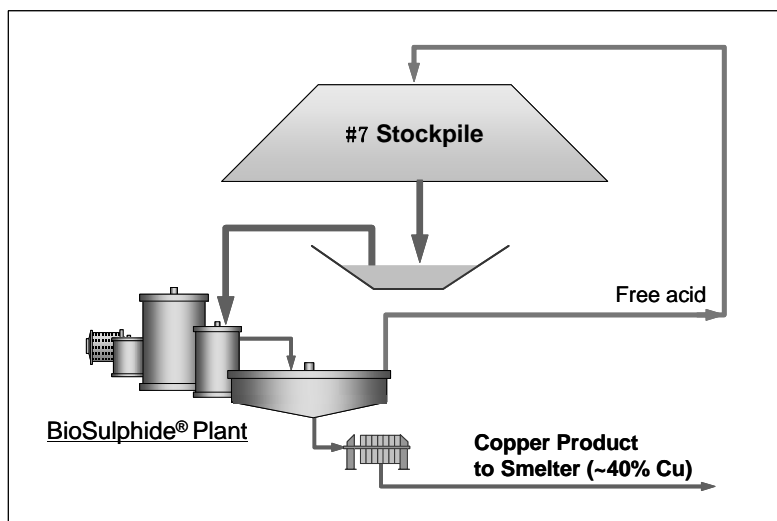


Fig. 4 Simplified flowsheet showing the use of biogenic sulphide for copper recovery at Bisbee

Precipitation of copper from the drainage is rapid and efficient, with copper recoveries consistently greater than 99.5% from the feed solution containing copper in the range 220 to 360 mg/L at a flow currently in the range of 8,000 to 9,000 m³ per day. The copper sulphide product is thickened and dewatered using conventional equipment, with the plant effluent containing free acidity returned to the

stockpile. The filtered concentrate, containing typically 40-45% copper, is shipped to the Phelps Dodge-owned smelter in Miami, Arizona for processing to metal. Payback on the US\$3.2 million plant is expected to be less than 3 years.

BIOGENIC SULPHIDE FOR CYANIDE RECYCLE AND COPPER RECOVERY

Sulphide-Based Processes for Cyanide and Copper Recovery

In the SART process, the cyanide associated with the copper (and zinc, if present) cyanide complexes is released, allowing it to be recycled back to the leach process as free cyanide. Copper is also recovered as a valuable, high-grade (~70% Cu) Cu_2S by-product. Cyanide recycling allows the leach circuit to be operated at higher cyanide levels, maximizing leach efficiency and minimizing copper deportment to gold electrowinning. The SART process uses chemical sulphide ions from reagents such as NaHS, to precipitate copper and convert cyanide to HCN gas, under weakly acidic conditions (pH 5).

The basic chemistry of the SART process, which was developed in the 1990s (MacPhail, et al., 1998) is identical to the MNR process, which was extensively tested in the 1980s (Potter, et al, 1986). The difference between the two processes is in the addition of a clarifier thickener to the circuit in the SART process to improve physical handling of the precipitate. In the MNR process, the Cu_2S precipitate is pumped directly from the primary reactor to a pressure filter as a low-density slurry, whereas in the SART process, the volume of slurry reporting to the pressure filter is greatly decreased. Both the MNR and SART processes have been piloted, and a full-scale SART plant was built and successfully commissioned at Newcrest's Telfer operation in Western Australia in ~2001. After a 5-year period of care and maintenance, a new circuit was implemented and the Telfer plant was restarted in 2006, with planned recommissioning of the SART circuit in 2007.

BioSulphide® Process for Cyanide and Copper Recovery

The SART process, as originally developed, uses chemical sulphide ions from reagents such as NaHS. Chemical sulphide can be replaced by lower cost biogenically-produced hydrogen sulphide, which has the added advantage of lowering the acid demand by one third for copper cyanide treatment and half for zinc cyanide. A simplified process flowsheet in which biogenic sulphide replaces chemical sulphide in the SART process is shown in Fig. 5.

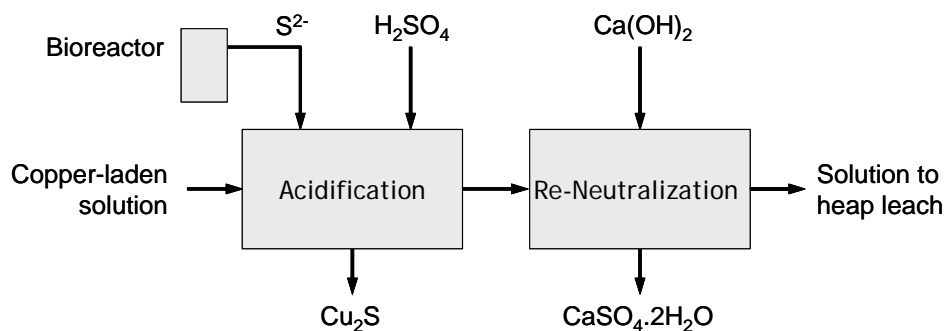
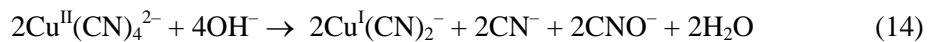


Fig. 5 Simplified diagram showing the SART process for copper recovery and cyanide recycle, with biogenic sulphide replacing chemical sulphide

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The SART process is ideally suited to heap leach operations, where barren solution (after gold recovery) is recycled directly to leach because cyanide is not pre-concentrated prior to recycling. Application to copper cyanide-rich tailings from a CIP or CIL plant requires prior solid/liquid separation using either filtration or counter-current decantation (CCD). For maximal cyanide recovery, the wash solution used in CCD or filtration must be low in cyanide, and the wash waters must also be treated, producing excess water with lower cyanide tenor, that can be directed to a heap leach operation if present.

Economic benefits of the SART process arise from the recycled cyanide, which reduces the cyanide addition requirement, and the saleable high-grade copper sulphide product. While the process allows operation at increased cyanide tenors, allowing for increased copper leaching and recovery, this comes at a cost when copper minerals in an oxidized state (e.g., covellite, CuS) are leached, due to the oxidation of one mole of cyanide per mole of copper (although the actual existence of the copper (II) cyanide complex remains in question):



An example of the potential economic benefit of a biogenic SART process was reported previously (Lawrence, et al., 2007); using NaHS, the operating costs for reagents, power and labour for treatment of a barren leach solution containing 250 mg/L Cu and 310 mg/L WAD cyanide in a SART circuit can be estimated to be \$0.40 per m³, using H₂SO₄, NaHS and Ca(OH)₂ costs of \$100/t, \$1000/t and \$250/t, respectively. Data from commercial BioSulphide[®] plants for sulphate waters demonstrates that costs of the sulphide reagent are further reduced when compared with use of NaHS. Moreover, acid consumptions are significantly reduced via utilization of the additional proton in the H₂S reagent produced biogenically. Assuming recoveries of 95% cyanide and 99% copper, unit costs of NaCN and copper of \$0.69/lb and \$2.50/lb, respectively, and a net smelter return of 85% for sale of the copper, revenues of \$1.98 per m³ can be estimated. Half of this revenue stems from the sale of copper sulphide, illustrating the potential added value of the leachable copper in a gold ore. By comparison, the cost of cyanide detoxification to treat a bleed stream using, for example, the SO₂/Air process ranges from \$1.50/kg NaCN to \$3.00/kg NaCN, depending on the method used and the presence and concentration of other species in the leach liquor. Under the most favourable circumstances, the cost of cyanide detoxification in the above hypothetical example would be about \$0.90/m³ of heap leach liquor treated. Therefore, the true benefit of the SART process with current reagent costs and commodity pricing is expected to be in excess of \$2.00/m³ of heap leach liquor treated.

The capital cost of a SART plant will be higher than a cyanide detoxification plant, but this will be more than offset by the revenues generated by copper recovery and the savings realized by cyanide recycle, allowing for a short payback time on the incremental capital.

New Projects – La Jojoba and Lluvia de Oro in Mexico

BioteQ is currently working with Columbia Metals Corporation Ltd., Canada, to apply its sulphide generating and precipitation technology in a SART circuit at both of Columbia's gold projects (La Jojoba and Lluvia de Oro) in northern Mexico. Processing of ores from both mines has presented challenges owing to the presence of cyanide-soluble copper.

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The Lluvia de Oro project will be the first of the two projects to go into production. The Lluvia de Oro mine is located approximately 13 km northwest of the town of Magdalena de Kino, Sonora, Mexico. The low-grade gold ore deposit, which contains a significant quantity of copper mineralization, has been previously worked by others, but lower gold prices, together with high cyanide consumption and diminishing carbon adsorption capacity resulting from the build-up of copper in the leach solution, led to discontinuation of operations in the late 1990s. Columbia Metals is planning to restart the exploitation of the deposit by open-pit mining, crushing and cyanide heap-leaching followed by carbon adsorption in an ADR (adsorption-desorption-recovery) plant. Gold doré will be produced on site following carbon stripping and electrowinning. It is the development of the SART process that now provides both Columbia Metals and BioteQ the opportunity for successful operations at this site through the recovery of saleable copper and the ability to recover cyanide from the barren leach solution.

In the first phase of the project, a portion of the existing heap-leach pad will be re-crushed, placed on a new pad and subjected to cyanide leaching. In the second phase of the project, fresh ore will be mined and crushed prior to being placed on the pad. A schematic of the overall project flowsheet is shown in Fig. 6.

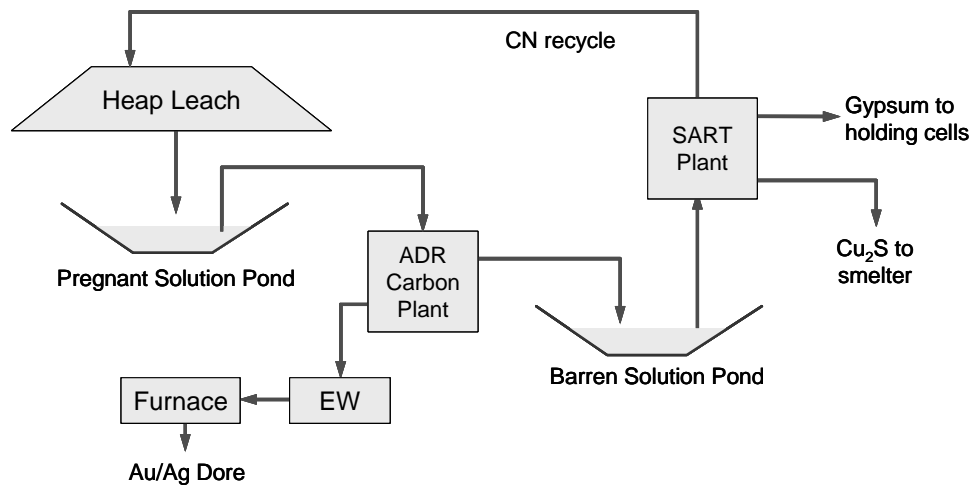


Fig. 6 Overall process flowsheet showing gold production and application of SART process for copper recovery and cyanide recycle planned for the Lluvia de Oro project

Fig. 7 provides a more detailed schematic of the SART process using biogenic sulphide in place of chemical sulphide reagent. In the configuration shown in Figs. 6 and 7, the feed to the SART plant will be taken from the discharge of the carbon ADR plant, with the solution from the SART plant returned to the heap leach. However, depending on a number of process factors, the feed to SART could be taken from the pregnant solution pond and with the SART plant effluent passing to the carbon ADR plant if it is shown that gold recovery can be optimized. The copper sulphide product will be recovered in a thickener – pressure filter circuit and will be shipped to a copper smelter in Mexico or the USA.

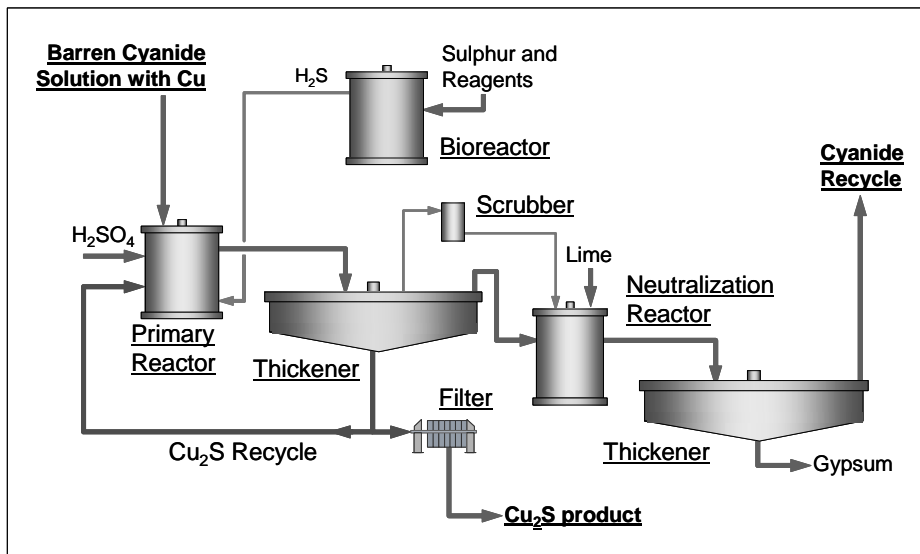


Fig. 7 Flowsheet showing the use of biogenic sulphide to replace chemical sulphide in the SART process for cyanide recycle and copper recovery in gold-copper ore processing

Gold production at the La Jojoba property, located approximately 4 km away from Lluvia de Oro, is planned to start at a later date. Processing of pregnant solution from La Jojoba into the plant at Lluvia de Oro is a potential feasible option.

CONCLUSIONS

The challenges surrounding the treatment of gold-copper ores are many and varied, including excessive cyanide consumption, increased cyanide detoxification costs and the environmental downside due to copper-stabilized WAD cyanide in tailings dam supernatant solutions. In these cases, the gold operator is typically forced to integrate an expensive cyanide oxidation circuit on the tailings stream. To a large extent, these challenges can be overcome by inclusion of a biogenic SART circuit, where the excess cyanide both leaches more recoverable saleable copper and is recycled, and the tailings are rendered benign. Importantly, in an age where detoxification costs are often considered more disposable than routine maintenance costs, a biogenic SART circuit can potentially almost completely offset the cost of achieving tailings stream Cyanide Code compliance in the case of gold-copper ores.

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REFERENCES

- Adams, M.D., Removal of cyanide from solution using activated carbon. *Minerals Engineering*, 1994, **7(9)**, 1165-1177.
- Adams, M.D., Swaney, S.J., Friedl, J. and Wagner, F.E., Preg-robbing minerals in gold ore and residues. In *Hidden Wealth*. South African Institute of Mining and Metallurgy, Johannesburg, 1996, pp. 163-172.
- Adams, M.D. Aspects of the mineralogy and chemistry of gold-copper and copper-gold ores. In *Processing of Gold-Copper and Copper-Gold Ores*, ed. M.D. Adams. Oretest Pty Ltd, Perth, 2000, pp. 17-42.
- Adams, M.D. and Kyle, J.H., Precipitation of cyanide as $\text{Cu}_2\text{Fe}(\text{CN})_6$ compounds from cyanidation and detoxification circuits. In *Minprex 2000*. Australasian Institute of Mining and Metallurgy, Carlton, Victoria, 2000, pp. 201-206.
- Bennett, C.A., Crathorne, E.A. and Edwards, R., Prevention of copper dissolution during cyanidation of gold ores, *S. Afr. Pat.* 89/8235, April 30, 1991.
- Butcher, D.J., Ammoniacal cyanide leaching for recovery of gold from TORCO tailings – Akjoujt Mauritania. In *Randol Gold Forum '95*, Randol International, Golden, Colorado, 1995, pp. 231-238.
- Carlisle, J.C. and Mitchell, A.H.G., Magmatic arcs and associated gold and copper mineralisation in Indonesia. *J. Geochem. Explor.*, 1994, **50(1-3)**, 91- 142.
- Drok, K. and Ritchie, I., An investigation of the selective leaching of gold over copper using ammoniacal cyanide. In *World Gold '97*, Australian Institute of Mining and Metallurgy, Melbourne, 1997, pp. 145-151.
- Fleming, C.A., Grot, W. and Thorpe, J.A., Hydrometallurgical extraction process. *U.S. Pat.* 5,411,575. May 2, 1995. 8 pp.
- Gibbons, T., International cyanide management code. In *Advances in Gold Ore Processing*, ed. M.D. Adams. Elsevier, Amsterdam, 2005, pp. 182-200.
- Goldblatt, E., Recovery of cyanide from waste cyanide solutions by ion exchange. *Ind. Eng. Chem.*, 1956, **48(12)**, 2107; 1959, **51(3)**, 241.
- Hunt, B., Process of precipitating and recovering precious metals from their solutions. *U.S. Pat.* 689,190, December 17, 1901. 1 pp.
- Lawrence, R.W., Kratochvil, D., Ramey, D., A new commercial metal recovery technology utilizing on-site biological H_2S production. In *Proceedings – HydroCopper 2005 – 3rd International Workshop on Copper Hydrometallurgy*. Santiago, Chile, November 23-25, 2005.
- Lawrence, R.W., Phillipe, R. and Fleming, C.A., Sulphide and ion-exchange technologies for metal recovery and water treatment in the copper mining industry. In *Proceedings – HydroCopper 2007 – 4th International Workshop on Copper Hydrometallurgy*. Viña Del Mar, Chile, May 16-18, 2007.
- MacPhail, P.K., Fleming, C.A. and Sarbutt, K.W., Cyanide recovery by the 'SART' process for the Lobo-Marte Project – Chile. In *Proceedings – Randol Gold Forum '98*. Randol International, Golden, Colorado, 1998, pp. 319-324.
- Muir, D.M., Vukcevic, S. and Shuttleworth, J., Optimising the ammonia-cyanide leaching process for copper-gold ores. In *Proceedings – Randol Gold Forum '95*. Randol International, Golden, Colorado, 1995, pp. 225-230.

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- Osseo-Asare, K., Xue, T. and Ciminelli, V.S.T., Solution chemistry of cyanide leaching systems. In Precious Metals Mineralogy, Extraction and Processing – Proceedings of an International Symposium. 1984, pp. 173-197.
- Potter, G.M., Bergmann, A. and Haidlen, U., Process of recovering copper and of optionally recovering silver and gold by leaching of oxide and sulphide - containing materials with water-soluble cyanides. U.S. Pat. 4,587,110, May 6, 1986. 6 pp.
- Riveros, P.A., Molnar, R.E. and McNamara, V.M., Alternative technology to decrease the environmental impact of gold milling. CIM Bull., 1993, 1993, 167-171.
- Sceresini, B., Gold-copper ores. In Advances in Gold Ore Processing, ed. M.D. Adams. Elsevier, Amsterdam, 2005, pp. 789-824.
- Stevenson, J., Botz, M., Mudder, T., Wilder, A., Richins, R. and Burdett, B., Recovery of cyanide from mill tailings. In The Cyanide Monograph, eds. T.I. Mudder and M.M. Botz, First Edition, Mining Journal Books, London, 1998, pp. 241-264.