



## Towards industrial implementation of glycine-based leach and adsorption technologies for gold-copper ores

J. J. Eksteen, E. A. Oraby, B. C. Tanda, P. J. Tauetsile, G. A. Bezuidenhout, T. Newton, F. Trask & I. Bryan

To cite this article: J. J. Eksteen, E. A. Oraby, B. C. Tanda, P. J. Tauetsile, G. A. Bezuidenhout, T. Newton, F. Trask & I. Bryan (2017): Towards industrial implementation of glycine-based leach and adsorption technologies for gold-copper ores, Canadian Metallurgical Quarterly, DOI: [10.1080/00084433.2017.1391736](https://doi.org/10.1080/00084433.2017.1391736)

To link to this article: <http://dx.doi.org/10.1080/00084433.2017.1391736>



Published online: 26 Oct 2017.



Submit your article to this journal [↗](#)



View related articles [↗](#)



View Crossmark data [↗](#)



## Towards industrial implementation of glycine-based leach and adsorption technologies for gold-copper ores

J. J. Eksteen <sup>a</sup>, E. A. Oraby<sup>a</sup>, B. C. Tanda <sup>a</sup>, P. J. Tauetsile<sup>a</sup>, G. A. Bezuidenhout<sup>a</sup>, T. Newton<sup>a,b</sup>, F. Trask<sup>b</sup> and I. Bryan<sup>b</sup>

<sup>a</sup>Gold Technology Group, Western Australian School Mines, Curtin University, Perth, Australia; <sup>b</sup>Mining and Process Solutions Pty Ltd, Australian Minerals Research Centre, Waterford, Australia

### ABSTRACT

The technology to selectively leach gold, silver and base metals from ores, concentrates, and wastes, using an alkaline glycine solution, has initiated significant interest in using the new technology in various environments such as *in situ*, in-place, dump, heap, and vat and agitated tank leaching. It has been shown that glycine acts synergistically with a number of other lixiviants to lower the net consumption of the other lixiviants while allowing low-cost glycine solution recovery. Glycine is a non-toxic, stable, environmentally benign reagent that is available in bulk industrial quantities. It has the ability to dissolve most copper oxide and sulphide minerals, as well as native copper, whilst not interacting with acid-consuming gangue nor dissolving iron and various or ubiquitous gangue elements. It acts synergistically with small amounts of cyanide to leach gold-copper ores at leach rates higher than either glycine or cyanide on their own, while significantly reducing cyanide consumption and eliminating detoxification requirements. The leaching behaviour of various glycine-based systems will be reviewed, followed by the evaluation of the adsorption of gold onto activated carbon. Where the economics merit it, copper can be easily recovered using solvent extraction or sulphide precipitation.

### RÉSUMÉ

La technologie de lixiviation sélective de l'or, de l'argent et des métaux de base à partir de minerais, de concentrés et de déchets à l'aide d'une solution alcaline de glycine a suscité un intérêt considérable pour l'utilisation de la nouvelle technologie dans divers environnements tels que la lixiviation in-situ, in-place, de décharge, en tas, en cuve et en cuves agitées. Il a été montré que glycine agit en synergie avec un certain nombre d'autres lixivants pour abaisser leurs consommations nette tout en permettant la récupération de la solution de glycine à faible coût. La glycine est un réactif non toxique, stable et sans danger pour l'environnement, disponible en grandes quantités industrielles. Il a la capacité de dissoudre la plupart des minéraux d'oxyde de cuivre et de sulfure, ainsi que du cuivre natif, sans interagir avec la gangue consommant de l'acide, ni dissoudre le fer et divers omniprésents éléments de la gangue. Il agit en synergie avec de petites quantités de cyanure pour lixivier les minerais d'or-cuivre à des taux de lixiviation supérieurs à ceux de la glycine ou du cyanure utilisé seul, tout en réduisant considérablement la consommation de cyanure et en éliminant les exigences de détoxification. Le comportement de lixiviation de divers systèmes à base de glycine sera revu, suivi de l'évaluation de l'adsorption de l'or sur du charbon actif. Là où l'économie le mérite, le cuivre peut être facilement récupéré en utilisant l'extraction par solvant ou la précipitation au sulfure.

### ARTICLE HISTORY

Received 25 April 2017  
Accepted 2 October 2017

### KEYWORDS

Glycine; copper; silver; gold; cyanide; leaching; solvent extraction; alkali; amino acid

## Introduction

Gold-copper deposits are often notorious for their mineralogical complexity and geometallurgical variability in both copper and gangue mineralisation. It is particularly challenging to find economically feasible solutions for low-grade deposits with gold grades below  $0.8 \text{ g t}^{-1}$  and copper grades below 0.3%, where mining normally has to be on a massive scale with very large capital investment. Conventional deposits are often characterised by a

weathered or oxidised upper zone followed by a zone of supergene enrichment with mixed oxides and sulphides and a pyrite-chalcopyrite predominant hypogene zone as one progresses in depth. Gold and/or silver is often found in all three of these domains. This progression has often led to different processing approaches for the various zones and geological domains, in particular (sulphuric) acid leaching of the oxide ores (followed by cyanidation for precious metals) and grinding and flotation of

**CONTACT** J. J. Eksteen  jacques.eksteen@curtin.edu.au  Gold Technology Group, Western Australian School Mines, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

© 2017 Canadian Institute of Mining, Metallurgy and Petroleum

the sulphide ores to produce a concentrate for smelting. Ore derived from the supergene enrichment zone is particularly problematic given its mixed nature, its poor flotation response (even after NaHS conditioning) and the high content of both acid-consuming gangue and cyanide-soluble copper minerals. Precious metals are often associated with all or many of the zones, and domains of the deposit and processing for optimal copper recovery often creates conflicting requirements to optimal recovery of the precious metals. Even minerals with a good flotation response such as chalcopyrite, may be finely disseminated in pyrite and/or associated with arsenic/antimony-bearing enargite or tennantite and tetrahedrite, causing poor gold recovery to concentrate if smelter penalty elements are to be suppressed. Acid leaching is particularly problematic if the copper minerals are associated with high amounts of acid-consuming gangue and gel-forming silicates. Milling and flotation often becomes uneconomic if the combined copper and gold grades become too low and the level of dissemination with associated pyrite becomes fine, making it difficult to prepare a concentrate of sufficient grade at an economic recovery.

The intent of this paper is to review the research the Gold Technology Group (GTG) of Curtin University, Australia, has done, often in collaboration of its commercialisation partner, Mining and Process Solutions Pty Ltd (MPS). Some unpublished information is presented together with some of the salient findings mentioned in prior research. The foundation of this work is specified in two pending patents [1,2] although a significant corpus of unpublished know-how has been accumulated over the preceding and subsequent years. The review below discusses some results covering the leaching and the metals recovery from solution.

The process relates to the use of an amino acid (typically glycine), as a lixiviant for copper, silver, gold, nickel, cobalt, zinc and lead, under alkaline conditions, using oxygen, air or hydrogen peroxide as oxidant. Catalytic or synergistic amounts of other ions may be present, but typically in far lower concentrations than the amino acid.

Glycine ( $\text{NH}_2\text{-CH}_2\text{-COOH}$ ) is a stable amino acid that has various aqueous ionic forms, i.e. the cationic glycinium ion ( $\text{NH}_3\text{-CH}_2\text{-COOH}^+$ ) in acidic solutions, the neutral zwitterion ( $\text{NH}_3^+\text{-CH}_2\text{-COO}^-$ ), and the anionic glycinate ( $\text{NH}_2\text{-CH}_2\text{-COO}^-$ ) ion in alkaline solutions, demarcated by two  $\text{pK}_a$  values at 2.34 and 9.6. While glycine can be decomposed by some micro-organisms or destroyed by strong oxidants, it is stable in the water stability band in the  $\text{pH-E}_h$  diagram at alkaline pH in the anionic glycinate form. Glycine has a high solubility in water of around  $250 \text{ g L}^{-1}$  at  $25^\circ\text{C}$ , a density of

$1.607 \text{ kg t}^{-1}$ , molar mass of  $75.07 \text{ g mol}^{-1}$  and a melting point of  $233^\circ\text{C}$  (with decomposition). It therefore has a much higher stability (as glycinate anion) than the cyanide or thiosulphate anions. It shows a low but measurable pH-dependent adsorption on clays (montmorillonite specifically) as indicated by Ramos and Huertas [3]. One should compare this to gold and silver cyanide complex preg-robbing on clays [4]. It forms moderately strong complexes with most chalcophile base metals and precious metals under appropriate pH, temperature and redox conditions.

Glycine (and other amino acids) has been shown to be able to dissolve gold, silver and gold-silver alloys, under alkaline conditions and at mildly elevated temperature, and copper has been found to be a catalyst during the dissolution process [5,6]. Oraby and Eksteen [6] have also shown the potential for activated carbon to be used as an adsorbent for gold and silver glycinate for precious metals recovery from solution. More information on adsorption is presented later in this paper. However, leach rates for alkaline glycine on its own, even at elevated temperature, is less than a third that of cyanide at room temperature, making it only a serious contender to cyanide for *in situ* leaching, heap leaching, or in some cases, vat leaching. However, in the presence of small amounts of cyanide (but zero free cyanide, i.e. starvation), the rates has also been shown to be as much as  $6\times$  that of cyanide only and  $18\times$  that of glycine only [7].

In addition it has been shown that copper minerals, such as oxides (cuprite), native copper and various sulphide (chalcocite, djurleite, bornite, covellite and chalcopyrite) can be effectively dissolved from a gold-copper gravity concentrate in the presence of alkaline glycine and an oxidant at room temperature [8]. Subsequently it was also shown that various copper oxides (cuprite, malachite, azurite and chrysocolla) can all be dissolved in alkaline glycine, although copper extraction from chrysocolla tends to be poor compared to the other oxide minerals [9]. Tanda et al. also showed that the copper (cupric) glycinate species can be effectively measured in alkaline solutions using UV-visible spectrometry. Furthermore Eksteen et al. [10] have shown that glycine can be used to leach copper from chalcopyrite-bearing concentrates or ores under alkaline conditions. Chalcopyrite concentrate leaching, under atmospheric pressure is shown to be significantly enhanced using a combination of mildly elevated temperature ( $50\text{--}60^\circ\text{C}$ ), ultra-fine grinding and/or alkaline preoxidation (also at atmospheric pressure). Eksteen et al. [10] then also introduce a few flowsheets involving chalcopyrite leaching, where copper recovery from solution is achieved by either solvent extraction or by sulphide precipitation as

a pure, coarse-grained, covellite precipitate. Glycine is retained in the aqueous solution in all cases and can be recycled after metal recovery from solution, if economically worthwhile.

Tanda et al. [11] presented further research on the solvent extraction and elution of copper glycinate from alkaline glycinate solutions using Mextral 84H (similar to LIX 84-I) and Mextral 54-100 (similar to LIX 54-100) on alkaline leachates derived from either copper oxide or sulphide sources. Extraction of copper into the organic phase has been shown to happen via the copper ion only, and neither the complex nor any glycinate dissolved into the organic phase. Effective extraction and stripping could be achieved in single stages. It was feasible to strip into a conventional acidic electrolyte consisting of 180 g L<sup>-1</sup> sulphuric acid and 30 g L<sup>-1</sup> copper ions with a 5 g L<sup>-1</sup> increment in copper concentration in the electrolyte.

Oraby et al. [12] performed leach research using glycine solutions with small amount of cyanide to leach various gold-copper ores and gold-silver-copper concentrates. The experiments were carried out in conventional bottle rolls operating with 50% solids, real ores, and at room temperature and no further oxygen addition. In all cases, it was shown that the cuprous weak-acid-dissociable (WAD) cyanide rapidly approximated zero, whereas all the copper is essentially present in its cupric (glycinate) state, as supported by UV-vis spectral analysis. Leaching was rapid in all cases with much higher rates and gold (and copper and silver) recovery to solution than for cyanide-only systems, even at high cyanide dosages. Oraby et al.'s paper demonstrated the potential of using such a synergistic system of glycine in the presence of insignificant to zero free cyanide by the end of the leach, effectively eliminating cyanide detoxification or recovery requirements. Often 75–95% of the cyanide consumption may be eliminated using glycine as the predominant lixiviant and cyanide as the rate accelerant. Glycine's stability under alkaline conditions makes it feasible to recover, recycle and reuse the barren glycinate solution after metal recovery from solution, if filtration costs can be justified. Dry [13] evaluated the high-level techno-economics of a few flowsheets for gold extraction from ores with nuisance copper minerals and showed the significant economic potential that alkaline glycine-based processing has for the recovery of gold from polymetallic resources compared to conventional cyanidation.

This paper will discuss the extraction of gold and copper from various ore and concentrate resources and present the information under the following themes:

- Leaching behaviour in cyanide-free glycine environments

- Leaching behaviour in alkaline glycine under cyanide-starved conditions (no free cyanide).
- Gold adsorption onto activated carbon from alkaline glycinate solutions
- Copper recovery from solution
- High -level cost impacts

### Leaching in cyanide-free environments

Eksteen and Oraby [5] and Oraby and Eksteen [6] have shown that gold, silver and gold-silver alloys can be leached in alkaline glycinate solutions. In the absence of catalysts, it was found that the leach solution had to be heated to around 50–60°C to obtain practical leach rates. However, even at these temperatures, leach rates obtained were still around a third of cyanide leach rates at ambient temperature (23°C). In studies on pure gold sheets, leach rates of 0.322 μmol m<sup>-2</sup> s<sup>-1</sup> (0.228 g m<sup>-2</sup> h<sup>-1</sup>) could be obtained at a pH of 11 at 60°C using 1% hydrogen peroxide solution as oxidant and a 0.5 M solution of glycine. Leaching of gold from a 50 wt-% gold-silver alloy was found to be 5.96 times faster than from pure gold under the same leach conditions. Silver leaching was 7.96 times faster than pure gold under the same leach conditions. In these tests there was no catalyst such as cyanide, copper ions or lead nitrate. Eksteen and Oraby [6] has shown that, in the presence of 4 mM (~0.25 g L<sup>-1</sup>) Cu<sup>2+</sup> ions, gold leaching occurred at >9 times the average rate compared to the leach rates in the absence of copper (at 30°C, pH of 11, 0.1% H<sub>2</sub>O<sub>2</sub> and 0.1 M glycine). It is therefore clear that, in the absence of stronger oxidants such as H<sub>2</sub>O<sub>2</sub>, elevated temperatures and the presence of some copper catalyst, agitated tank leaching of gold would not be feasible. *In situ* and heap leaching may be feasible. Heated heap leaching, where use is made of solar ponds and solar heating and insulating plastic sheeting may be beneficial [14].

Tanda [15] performed some simulated column leach tests using alkaline glycine on a low-grade sulphur-rich ore with copper predominantly mineralised as chalcocopyrite. The semi-quantitative bulk mineralogy of the ore tested is given in Table 1. The chemical assays of the ore are presented in Table 2.

While one may have considered flotation of this ore to make a gold bearing flotation concentrate, the grinding energy requirement per tonne Cu or ounce Au is quite significant, given the Cu and Au grade of the ore. One may therefore consider a heap leach. Low-grade chalcocopyrite heap leaches are known to be particularly hard. For this ore it was not known how the gold was distributed (if it was sufficiently exposed). Heap simulation experiments were performed in columns fabricated

**Table 1.** Bulk mineralogy of Au-Cu ore.

Phase	%
Chalcopyrite	~1
Pyrite	43
Spinel group	2
Quartz	32
Chlorite	10
Mica	10
Gypsum	2

**Table 2.** Chemical assay of high sulphur Cu-Au ore.

Element	Assay	Element	Assay
Au ( $\text{g t}^{-1}$ )	0.65	K (%)	0.11
Ag ( $\text{g t}^{-1}$ )	12.00	Na (%)	0.14
Cu (%)	0.37	Mn (%)	0.16
Fe (%)	23.75	Ti (%)	0.09
Pb (%)	0.11	Al (%)	2.08
Zn (%)	1.13	Ba (%)	0.02
Ni (%)	0.01	P XRF (%)	0.03
Ca (%)	1.13	S XRF (%)	19.20
Mg (%)	1.46	S LECO (%)	19.70

from 5 mm thick Plexiglas. The column height was 1000 mm while the internal diameter was 90 mm. The bottom of the column had a support flat base with multiple holes for solution discharge while holding the solids. The support base also contains an air inlet which distributes air through 0.5 mm holes inserted along the diameter of the column base. The column was equipped with a lid to minimise solution loss. The lid contained two holes, one for solution inlet and the other for air escape. Washed and dried crushed quartz was placed at the bottom of the column for support and air distribution. The ore was then added to the column and quartz was again placed on top of the ore to assist in the homogeneous distribution of the leaching solution. The ore was a crushed material with a  $P_{80}$  of 6 mm and a  $P_{100}$  of 8 mm. Fines below 1 mm were removed by screening (prior to assaying and mineralogy). The leaching solution was delivered to the top of the column by a peristaltic pump. Solution percolated through the ore by gravity and into a collection container from where it was re-circulated through a side loop by the pump. The leaching solution at pH 11 containing a glycine concentration of 0.5 M was circulated at a rate of  $2.2 \text{ L m}^{-2} \text{ min}^{-1}$  at room temperature. Air was injected at the bottom of the column at a rate of  $0.1 \text{ L min}^{-1}$ . After 48 days of liquor circulation, 53.6% Cu extracted. However, gold dissolution was noted to be slow with 7.6% Au leached after 48 days.

Further tests were performed on another low-grade Cu-Au ore with a mineral composition as depicted in Table 3 and an assay in Table 4. These were done to better understand the role of temperature, oxygenation and glycine concentration. In this case, the ore is very low-

**Table 3.** Mineralogy of low-grade, low sulphur gold ore with nuisance copper.

Minerals	Mass [%]	Minerals	Mass [%]
Actinolite	2.45	Ilmenite	0.05
Albite	0.01	Kaersutite	0.71
Ankerite + clay(Fe)	0.01	Magnesiogedrite	0.77
Anorthite	0.32	Muscovite	0.68
Apatite	0.22	Orthoclase	4.63
Biotite	4.64	Plagioclase	50.03
Calcite	0.02	<b>Pyrite</b>	<b>0.21</b>
<b>Chalcopyrite</b>	<b>0.23</b>	<b>Pyrrhotite</b>	<b>0.27</b>
Ferro-Actinolite	0.05	Quartz	32.12
Ferrosaponite	0.08	Rutile	0.02
Garnet-Pyrope	0.86	Scheelite	0.01
Haematite/magnetite	0.14	Zircon	0.03
Titanite	0.71	The rest	0.04
Tschemakite	0.68	Total	100
Hornblende	0.01		

grade with respect to both copper (0.15%) and gold ( $0.51 \text{ g t}^{-1}$ ). The ore was ground to a  $P_{80}$  of 75  $\mu\text{m}$  and was leached in an agitated beaker with oxygen addition with a pulp containing 50% solids.

At the 75  $\mu\text{m}$  grind and 50% solids content it was found that, at room temperature 65% of the Cu and 53% of the gold dissolved, but only after 528 h of leaching, making it clear that leaching at room temperature is slow. However, gold leach rates tended to increase over time whereas copper leach rates tended to decrease. The pH had a marked influence on the leach rates at room temperature: Increasing the pH in steps from 8, 9, 10, through to 11, increased the Cu extraction from 18.9 to 41.8, 51.8 and 55.6%, respectively, while gold extractions to on the values 2.8, 4.4, 7.8 and 37.6% when glycine initial concentration of 0.5 M was used. Changing the pH from 10 to 11 therefore had a marked effect on gold and copper leach rates. The effect of temperature is also very pronounced. The effect of temperature on copper and gold dissolution from Cu-Au ore C was studied at 25 and 60°C. The glycine concentration was kept at 0.5 M and oxygen flow rate was maintained at  $0.3 \text{ L min}^{-1}$ . Higher temperature favoured copper dissolution with a 66% copper extraction at 60°C while 41% was dissolved at 25°C after 96 h. Gold dissolution was 15.4% at 60°C and only 8.5% at 25°C after 96 h.

In concluding the section on glycine only (non-cyanide) leaching, it appears that leach rates using alkaline glycine only (in the absence of catalysts) tend to be slow. Temperature and pH had significant impacts on both Cu and Au leaching, with mildly elevated temperatures (60°C and pH of around 11 favouring optimal extraction rates). The leach rates, even at elevated temperature remain far too slow for agitated tank leach systems, but it appears to have potential for heap leach or *in situ* leach systems, when cyanide cannot be used. It also offers potential for smaller scale vat leach operations where production scale and available leach residence

**Table 4.** Assay of low-grade Cu-Au ore.

Element	Au (g t <sup>-1</sup> )	Cu%	As%	Fe%	Mg%	Al%	Si%	Ca%	S%	K%
<b>Assay</b>	0.51	0.15	0.01	3.64	1.76	8.00	30.3	3.22	0.37	1.39

time is appropriate for vat leaching. In all cases heating, e.g. through solar heating would be advisable.

### Leaching in cyanide-starved environments

One of the main deterring aspects in glycine-only (cyanide-free) environments is that adequate leaching rates that would be practical for agitated tank leaching (leach times less than 48 h) appear to be out of reach. However, in many cases, the biggest challenge with cyanide leaching is not the use of small quantities of cyanide, but rather the large quantities required to leach polymetallic ores (e.g. Cu-Au), and the significant amounts of weak-acid-dissociable (WAD) cyanide produced that needs to be destroyed. While recovery options such as SART has made inroads into cyanide recovery, practical cyanide recoveries seldom exceed 45%, the chalcocite precipitate produced tends to be ultrafine and reactive and the process is often plagued with water balance challenges due to the dilute nature of the recovered cyanide solution. The low cyanide recovery with SART can also be ascribed to formation of ferrocyanide, thiocyanate and cyanate. The presence of sulphuric acid in the proximity of a cyanide bearing solution also raises safety concerns. The GTG at Curtin University further developed a glycine-cyanide synergistic leach, where small amounts of cyanide (far below the amounts required to stabilise the metal cyanide complexes in solution) can be used to significantly accelerate the glycine leach process to within tank leach residence time frames. Oraby et al. [12] performed a series of bottle roll leach experiments at room temperature and with 50% solids. The initial pH was 11 and the leaching was carried out in 2.5 L Winchester bottles. They have found that a high grade (oxide) gold ore with 12.9 g t<sup>-1</sup> Au and 0.04% Cu leached readily. For a case of running with cyanide-only leach at 300 ppm cyanide, a gold extraction of only 5% was achieved after 48 h. When the cyanide concentration was raised to 1000 ppm (sufficient to complex all the cyanide-soluble metals), 42% of the gold leached. However, when the leach was performed with 300 ppm cyanide with 5 g L<sup>-1</sup> glycine, a leach extraction of 60% was achieved after 48 h (and 71% after 76 h). No free cyanide, nor any WAD cyanide was detected at the end of the leach time. Similar results were reported by Oraby et al. [12] for gold-silver-copper gravity concentrate and low-grade gold-copper ores. Depending on ore

type, cyanide consumption reductions of between 75 and 95% have been achieved.

The glycine-cyanide synergistic system has also been evaluated for heap leaching on a low-grade copper-gold ore with copper mineralised as chalcopyrite, bornite and chalcocite. The copper grade was 0.15% and the gold grade 0.67 g t<sup>-1</sup>. The ore was crushed to -12.5 mm and loaded in columns where it was irrigated with the lixiviant bearing solution for 14 days.

Table 5 presents the attributes and results for the leach tests.

The Cu and Au metal extraction from the ore (70% gold extraction, 38% Cu extraction) appears to be high in the glycine-cyanide environment, using only a fifth of the cyanide required compared to the cyanide-only case, whilst at the same time giving a 55.5% relative improvement in gold extraction and a 31% improvement in copper extraction. Even though glycine addition is 7.8 kg t<sup>-1</sup>, this is not the net glycine addition in a heap leach system as most (>92%) of the glycine remains in the aqueous solution and is recycled after the copper and gold has been removed from the pregnant leach solution. This implies that 'top-up' consumption is around 5% (0.39 kg t<sup>-1</sup>). Higher glycine consumption may be associated with a bleed from recycle back to leach to control impurities. However, through the judicious use of technologies such as nanofiltration, where it is economically justifiable, this can be minimised.

With cyanide costs around USD 2.38 and glycine costs around USD 1.70 (at the time of writing), there appears to be a cost incentive in terms of reagent cost savings, and an income potential in terms of improved recovery, and safety and environmental benefits (no free cyanide, WAD cyanide typically below 10 ppm).

**Table 5.** Simulated heap (column) leach of crushed Cu-Au ore with cyanide bearing solutions.

Test	Unit	Glycine-cyanide synergistic leach	Cyanide only
Head assay			
Au (g t <sup>-1</sup> )	g t <sup>-1</sup>	0.673	0.673
Cu (%)	%	0.15	0.15
Extraction			
Au	%	70%	45%
Cu	%	38%	29%
Cyanide addition	kg t <sup>-1</sup>	0.3	1.52
Glycine addition	kg t <sup>-1</sup>	7.79	
Lime addition	kg t <sup>-1</sup>	7.05	11.12

**Table 6.** Loading of gold from alkaline glycinate solutions onto activated carbon.

Experimental conditions, attributes	Glycine with cyanide (no Cu)	Cyanide, no glycine (with Cu)	Glycine, no cyanide (no Cu)	Glycine with cyanide (with Cu)
[CN], ppm	123	123	0	123
[Glycine], g L <sup>-1</sup>	5	0	5	5
[Au] <sub>initial</sub> , ppm	2	2	2	2
[Cu] <sub>initial</sub> , ppm	0	300	0	300
pH	11	11	11	11
Rotational speed, RPM	105	105	105	105
Loading time (h)	24	24	24	24
Loading kg <sub>Au</sub> /t <sub>carbon</sub>	4.59	3.43	22.36	4.24

### Adsorption of metals onto activated carbon in glycine environments

It is important to understand the extent of loading of gold and copper onto activated carbon to establish if carbon-based adsorption is still a sensible option for metal recovery from solution. Gold and silver glycinate complexes have been shown to have the potential to adsorb onto activated carbon [6]. This allows the consideration of carbon-in-pulp (CIP), carbon-in-leach (CIL), and carbon-in-column (CIC) technologies for alkaline glycine-based technologies (whether with cyanide or not).

Recent loading tests of gold onto activated carbon have shown that gold glycinate loads strongly onto activated carbon, as reflected in Table 6.

Therefore, gold loads very well as its glycinate complex in the absence of cyanide. The presence of cyanide and copper leads to decreased overall, but still acceptable loadings.

Significant further research on the adsorption and elution of gold and copper glycinate complexes from activated carbon has been performed, both in the presence and absence of cyanide, and in the presence of different pH modifiers (caustic soda versus milk-of-lime). These results will be published in future publications.

### Copper recovery from solution

Eksteen et al. [10] have shown that copper can be recovered from alkaline glycinate solutions using various technologies such as precipitation or solvent extraction (also discussed by Tanda et al. [11]). In addition ion-exchange technologies are seen to be feasible despite a general lack of research in this particular area. If copper is precipitated using NaHS, it precipitates as coarse-grained, easily filterable covellite. This may lead to gold co-precipitation and adsorption onto covellite. This is not inherently problematic as this material is ideal material for a copper smelter (it can be directly fed to the converter if required) as all copper smelters normally provide adequate

compensation for the precious metals. On the other hand, the copper can be co-adsorbed onto carbon and cold-eluted or pre-eluted, or recovered by solvent extraction, if copper recovery can be financially justified. Eksteen et al. [10] proposes a high-level flowsheet for the leaching of ore or concentrate containing chalcopyrite (and gold).

### High-level cost/economic impacts

To illustrate the economic impacts an example (calibrated on a real case) is discussed below. For this example, assume 15 million tonnes per annum of a supergene copper-gold reserve (containing mixed oxide and sulphide) is mined. The ore shows a poor response to flotation and a copper concentrate of sufficient grade cannot be produced at acceptable recoveries. The copper content of the ore is 0.15% and the copper is largely cyanide-soluble (80%), being a mixture of chalcocite, djurleite, covellite, bornite and chalcopyrite. The gold content of the ore is 0.8 g t<sup>-1</sup>. Gold recovery of 80% can be achieved during a glycine-cyanide heap leach. A high-level and simplistic comparison is presented below to illustrate the potential for using a glycine-cyanide synergistic heap leach rather than a conventional cyanide heap leach. For both leaching systems, gold is recovered by carbon adsorption and copper by sulphide precipitation from the pregnant heap leach solution. Due to the inherent value of the copper, detoxification requirements of the tails solution and the high cost of cyanide, the cyanide-only leach system operates a SART circuit for copper recovery and an AVR plant for cyanide recovery. Due to the formation of thiocyanate, cyanate and other metal cyanide complexes, only 40% of the cyanide is recovered through the AVR plant. The glycine-cyanide synergistic leach system runs a sulphide precipitation circuit followed by filtration. As the precipitation and solid-liquid-separation are also found in the SART process, it was thought that it would be conservative to keep the CAPEX and OPEX estimates the same for the reagent and copper recovery circuit. The glycine filtrate solution is recycled to the heap. A conservative glycine loss of 7.5% over the leach residence time relative to the copper production in the same time frame is allowed due to moisture losses with filter cake and to allow for partial glycine degradation over time in heap leach conditions. A commensurate amount of lime is added to match the glycine loss. Gold recovery is done by carbon from the solution before the copper precipitation step. AARL-based cyanide elution and electrowinning is the same for both routes. The complexities of managing copper co-adsorption onto the carbon is similar for both routes. For the sake

**Table 7.** Assumptions and inputs to cost model.

Factor	Unit	Cyanide only	Glycine-cyanide synergistic
Gold price	USD/oz	1250	1250
Copper price	USD/t	6000	6000
<b>Feed to plant</b>			
Tonnes milled	t/a	15,000,000	15,000,000
Cu content	%	0.15%	0.15%
Au content	ppm	0.8	0.8
<b>Metals value proposition</b>			
<b>Gold</b>	USD/t	25.72	25.72
<b>Cu</b>	USD/t	5.76	5.76
<b>Total</b>		31.5	31.5
<b>Value of Cu precipitate product</b>	%	80%	80%
<b>Cyanide recovery from AVR plant</b>	%	40%	40%
Base case all-in cost (prior to OPEX reduction due to glycine)	USD per tonne	28.00	28.00
Cyanide only – WAD management/SART/AVR cost	%	15%	
Glycine-cyanide precipitation and filtration cost	%		15%
<b>Total (overall) recoveries</b>			
Au	%	80%	80%
Cu	%	80%	80%
<b>Reagent requirements</b>			
Glycine	kg t <sup>-1</sup> ore milled	Cyanide only 0.0	Glycine-cyanide 0.3
Cyanide	kg t <sup>-1</sup> ore milled	2.22	0.25
Quicklime for glycine neutralisation	kg t <sup>-1</sup> ore milled	0.0	0.1

of simplicity and conservatism, it is assumed that both leaching systems run at the same operating cost (ex-reagents), although the SART/AVR circuit is more complex and expensive. The recoveries of both leaching systems were also assumed to be the same (we typically see >10% recovery improvements with the glycine-cyanide systems but did not allow for it here). Only the cost of reagents was compared to illustrate the significant saving potential on the margin. The high-level assumptions and calculations are presented in Tables 7–9. Table 7 provides the high-level inputs. One caveat to the numbers presented in Table 7 is that bleed streams from the recycle may lead to slightly higher glycine losses than is reflected below. Although we have not noticed any medium term degradation (over several months) at the pH's and E<sub>h</sub> employed in ore leaching over extended time periods, we note that this remains one aspect that needs to be fully reported on, although is outside the scope of this paper. It should be noted that degradation becomes much more significant when glycine is in its neutral zwitterion form (at pH < 9.6), or in its glycinium cation form (pH < 2.34). Finally, it is important to note that glycine can adsorb onto certain clays. Again, adsorption is more prevalent for the zwitterion and glycinium ion form than that for the glycinate form. However, these mechanisms may lead to glycine losses greater than what is reflected below. The base case of the all-in

costs is stated as equal amounts for the two cases. The OPEX improvement (and the reduction in AISC), expressed per tonne ore mined, is presented in Table 9. It is quite significant at US\$ 4.10 per tonne, given the conservative assumptions, and not valuing the improved safety, health and environmental impact benefits.

Table 8 lists the cost of reagents for a process using only cyanide versus one making use of the glycine-cyanide synergistic process.

Table 9 provides an estimate of the improvement in profit margin through improved reagent utilisation of the glycine-cyanide process versus the cyanide-only process. For conservatism no reduction in reagent recovery costs, lowered CAPEX or improved metal recoveries (both to be expected) are ascribed to the glycine-cyanide synergistic process compared to the cyanide-only process.

The margin of the operation can be more than doubled through the reagent cost saving potential. The cost saving at USD 4.10 per tonne ore is highly

**Table 9.** Estimation of change in profit margin.

Process	Unit	Cyanide only	Glycine-cyanide
Recovered value of gold and copper	USD/t <sub>ore</sub>	31.5	31.5
All-in cost per tonne	USD/t <sub>ore</sub>	28.0	28.0
Reagent cost differential	USD/t <sub>ore</sub>	0.0	-4.1
Profit margin	%	11%	24%

**Table 8.** Reagent consumption and cost.

Reagent	Cyanide only		Glycine-cyanide	
	Reagent unit price (USD/t)	Reagent consumption (kg t <sup>-1</sup> )	Reagent consumption (kg t <sup>-1</sup> )	Reagent cost (USD/t)
Glycine	1700	...	0.319	0.542
Cyanide	2,380	2.221	0.250	0.595
Quicklime	200	...	0.119	0.024

significant, particularly for this operation where the tonnage processed is 15 Mtpa, resulting in a net cash benefit of USD 61.5 million per annum. The glycine-cyanide synergistic leach has the potential to make ore bodies economically viable for extraction that would otherwise not be economically viable. Over and above the reagent consumption advantage, the leaching process is rather simple and straight forward, lowering capital requirements and operational cost. The entire leaching system is managed in a cyanide-starved environment and WAD cyanide/free cyanide values are low enough to comply with the cyanide code for disposal.

## Conclusions

This paper presented the leach and metal (gold and copper) recovery processes associated with a leach system consisting of an oxygenated aqueous alkaline solution with glycine as the lixiviant, either on its own, or with synergistic catalysts such as cyanide (in small amounts). These systems were compared to conventional cyanidation with respect to leach extraction, high-level kinetics, and adsorption onto activated carbon. A high-level profit margin improvement was calculated for illustrative purposes. It was found that the glycine-only systems suffered from slow kinetics, but that it may be suitable for heap, vat and *in situ* leaching. For agitated tank leaching, the cyanide-starved glycine synergistic leach is advised due to kinetics that are better than cyanide only (and glycine-only), the effective elimination of WAD cyanide and free cyanide and the significantly improved process economics, after reagent recovery is considered for both systems. There appears significant advantages to the application of the either the glycine-only or the cyanide-starved glycine processes to polymetallic gold-copper ores and concentrates.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

The authors would like to acknowledge the financial support provided by Curtin University. The research presented above falls under pending patents, owned by Curtin University.

## Notes on contributors

*Prof Dr J. J. Eksteen* is the Director of the Gold Technology Group affiliated with the Western Australian School of Mines (WASM) at Curtin University, Australia. Jacques is the Chair for Extractive Metallurgy and holds a PhD in metallurgical engineering.

*Dr E. A. Oraby* is a senior research fellow with the Gold Technology Group at Curtin University and holds a PhD in metallurgical engineering.

*Dr B. C. Tanda* recently received his PhD in metallurgical engineering from Curtin University.

*Ms P. J. Tauetsile* is a PhD student focusing on the adsorption of gold and silver glycinates onto activated carbon.

*Dr G. A. Bezuidenhout* is a Principal Metallurgist with the Gold Technology Group at Curtin University and holds a PhD in metallurgical engineering.

*Mr T. Newton* is the Operations Director of Mining and Process Solutions (MPS) Pty Ltd and is also a part-time PhD student of Curtin University.

*Mr F. Trask* is the Technical Director of Mining and Process Solutions (MPS) Pty Ltd.

*Mr I. Bryan* is the Managing Director of Mining and Process Solutions (MPS) Pty Ltd.

## ORCID

J. J. Eksteen  <http://orcid.org/0000-0002-5433-4845>

B. C. Tanda  <http://orcid.org/0000-0003-3485-4867>

## References

- [1] Eksteen JJ, Oraby EA. A process for precious metals recovery, PCT/AU2014/000877; 2014.
- [2] Eksteen JJ, Oraby EA. Process for selective recovery of chalcophile group elements. PCT/AU2016/050171; 2016.
- [3] Ramos ME, Huertas FJ. Adsorption of glycine on montmorillonite in aqueous solutions. *Appl Clay Sci.* 2013;80–81(2013):10–17.
- [4] Tremolada J, Dzioba R, Bernardo-Sánchez A, et al. The preg-robbing of gold and silver by clays during cyanidation under agitation and heap leaching conditions. *Int J Miner Process.* 2010;94:67–71.
- [5] Eksteen JJ, Oraby EA. The leaching and adsorption of gold using low concentration amino acids and hydrogen peroxide: effect of catalytic ions, sulphide minerals and amino acid type. *Miner Eng.* 2015;70:36–42.
- [6] Oraby EA, Eksteen JJ. The leaching and carbon based adsorption behaviour of gold and silver and their alloys in alkaline glycine-peroxide solutions. *Hydrometallurgy.* 2015a;152:199–203.
- [7] Oraby EA, Eksteen JJ. Gold leaching in cyanide-starved copper solutions in the presence of glycine. *Hydrometallurgy.* 2015b;156:81–88.
- [8] Oraby EA, Eksteen JJ. The selective leaching of copper from a gold-copper concentrate in glycine solutions. *Hydrometallurgy.* 2014;150:14–19.
- [9] Tanda BC, Oraby EA, Eksteen JJ. An investigation into the leaching behaviour of copper oxide minerals in aqueous alkaline glycine solutions. *Hydrometallurgy.* 2017a;167:153–162.
- [10] Eksteen JJ, Oraby EA, Tanda BC. A conceptual process for copper extraction from chalcopyrite in alkaline glycinate solutions. *Miner Eng.* 2017;108:53–66.

- [11] Tanda BC, Oraby EA, Eksteen JJ. Recovery of copper from alkaline glycine leach solution using solvent extraction. *Sep Purif Technol.* [2017b](#);187:389–396.
- [12] Oraby EA, Eksteen JJ, Tanda BC. Gold and copper leaching from gold-copper ores and concentrates using a synergistic lixiviant mixture of glycine and cyanide. *Hydrometallurgy.* [2017](#);169:339–345.
- [13] Dry M. A preliminary evaluation of alkaline glycine as an alternative to cyanide for gold extraction. ALTA 2016 Gold-PM Proceedings, 2016 May 21–28; Perth; Australia. 18 p.
- [14] Murray C, Platzer W, Petersen J. Potential for solar thermal energy in the heap bioleaching of chalcopyrite in Chilean copper mining. *Miner Eng.* [2017](#);100:75–82.
- [15] Tanda BC. Glycine as a lixiviant for the leaching of Low grade copper-gold ores [PhD thesis]. Australia: Western Australian School of Mines, Curtin University; [2017](#).