MAXIMISING THE VALUE OF GOLD DIAGNOSTIC LEACHING

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ABSTRACT
A detailed understanding of ore mineralogy and elemental deportment is required to select the optimal processing route for the extraction of valuable metals from ore, such as copper and gold. However, common ore characterization techniques, such as Mineral Liberation Analyser (MLA), are costly and time-consuming. Diagnostic leaching is potentially a cheaper and simpler alternative for the determination of the mineralogy and deportment of valuable minerals within an ore, involving the use of selected reagents and conditions to dissolve targeted minerals. Traditional diagnostic leaches currently used in processing plants worldwide, use sodium cyanide and sulfuric acid as reagents to provide details on copper and gold recoveries. This paper shows that these leaches can provide information on not only gold and nuisance copper recoveries for gold ores but also information on trace element recovery, mineralogical associations, reagent consumption and speciation. Leaches conducted on a gold ore sample set indicated variances in gold and copper recoveries, owing to the differing mineral concentrations and types. Low gold recoveries were attributed to the ore being refractory in nature. Chalcopyrite and pyrrhotite were found to contribute directly to the formation of thiocyanate. The importance of monitoring impurity element concentrations was demonstrated, since some sample leach liquors contained high toxic trace element concentrations. The use of additional information (reagent consumption, trace element recovery etc.) from diagnostic leach data may prove to be of great advantage in process design or optimisation.
INTRODUCTION

Geometallurgy uses mineralogical information and metallurgical characterisation to assess an orebody’s processability by populating a resource block model with characteristics to help evaluate different mining value options. Evaluation of an ore deposit for plant design or optimisation is critical before mining, with mineral grade and recovery being the most common attributes used in the model. However, population of the resource model with less traditional characteristics such as concentration of deleterious elements, mineral liberation, hardness or reagent consumption could be advantageous as such properties may have a significant impact on project viability.

Common characterisation techniques used in mine planning to determine ore mineralogy and elemental deportment include X-ray diffraction (XRD), electron microprobe analysis (EMPA), energy dispersive spectrometer equipped scanning electron microscopy (EDS-SEM), Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) and Mineral Liberation Analyser (MLA). These techniques may be costly and time-consuming.

Diagnostic leaching is a cost-effective and simple alternative to these mineralogical characterisation tools and uses low-cost, small-scale tests to characterise a large number of samples of low mass. Traditionally, these leach tests provide information on valuable element recovery, grade and may provide information on the mineralogy and deportment of valuable metals through the use of selected reagents to dissolve targeted minerals. The diagnostic leach can also provide additional information on reagent consumption, impurity and trace element deportment and solution speciation with the benefits of obtaining this information (often with minimal additional analysis) frequently being overlooked. The diagnostic leach could therefore not only be used as an alternative technique to traditional mineralogical analysis techniques but both commonly and less widely used characteristics of ore body samples could be obtained to populate the resource block model. It should be noted that calibration of the diagnostic leach may require mineralogical information on a small subset of samples before the tool can be applied to a large sample set from the deposit.

CSIRO researchers have been developing diagnostic leaching as a tool in the hydro- and geometallurgy fields with much of the focus being on copper and gold ores. Work has included the AMIRA International P843A Geometallurgical Mapping and Mine Modelling (GeM III) project where the project objective is to develop predictive hydrogeometallurgical indices to be incorporated into a resource block model for maximising the commercial value of an ore body and minimising the social and environmental impact of mining operations. Rapid, small-scale, cost effective tests and protocols have been developed for comparative ranking of attributes relevant to leach performance aimed mainly at copper and gold deposits e.g. leach index (relative indication of leach performance), recovery, impurity deportment, reagent consumption, effect of size/degree of liberation, mineralogy of samples for their relative ranking, heap hydrology and rheology. CSIRO is also involved extensively in other gold hydrometallurgy research, including the development of alternative lixivants to cyanide (particularly thiosulfate-based processes), deportment and management of cyanide species and trace elements, and cyanide destruction and recovery technologies.

Gold may occur in an ore as the native metal, as an alloy with other metals such as silver (electrum) and as a mineral in rare cases. The gold particles may be coarse and liberated with grinding or finely disseminated sub-microscopic particles in sulfide minerals such as pyrite and arsenopyrite (often referred to as solid solution or refractory gold). Gold ore recoveries depend on whether they are free-milling or refractory. The former type yield gold recoveries greater than 90%, while the latter yield recoveries below 80% owing to their high percentage content of sub-microscopic gold particles. Traditional gold diagnostic leaches use a combination of sodium cyanide and acid leaches with the dissolution of gold in aqueous cyanide solution taking place according to the Elsner equation in the presence of oxygen:

$$4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4[Au(CN)_2]^- + 4OH^-$$ (1)

Copper can exist in a number of forms within the ore, and occurs most frequently as a copper sulfide mineral, but can also exist within carbonates, oxides and more rarely, in its native metallic form. Traditional copper diagnostic leaches use sodium cyanide and sulfuric acid as leach reagents, with the dissolution of the copper sulfide mineral in these media being expressed by Eqs (2) and (3), respectively. The exact mechanism of these equations will vary according to the copper sulfide mineral and reaction conditions.
\[ Cu_S + 3xCN^- \rightarrow x[Cu(CN)_x]^2+ + yS^{2-} \]  

(2)

\[ Cu_S + 2H^+ \rightarrow xCu^{2+} + yH_2S \]  

(3)

This paper focuses on two commonly used lixiviants in diagnostic leaching, sulfuric acid and sodium cyanide, and discusses not only the traditional characteristics such as valuable and nuisance element recovery that can be obtained from samples from a copper gold sample set but also the sulfur speciation, reagent consumption and trace element recoveries that are obtained in the leaches. Where possible, links between hydrometallurgical and mineralogical properties are discussed. These highlight where leach data could be used as mineralogical predictors.

**METHODOLOGY**

**Cyanide Leach**

Eighteen sample types from a South American copper gold deposit were leached using the standard bottle roll leaching procedure at ambient conditions over a 24 hour period, with slurry sampling occurring at the 0.5, 1, 3 and 6 h intervals. 25 g samples (P80 -100 µm) were placed into a 1 L nalgene bottle along with 150 mL of 1.5 g/L sodium cyanide solution. The bottles had a perforated lid and provided a large head space to ensure sufficient oxygen supply. The bottle roller was set to approximately 200 rpm to ensure mixing yielded a uniform slurry. The pH remained above 9.5 for the duration of the leach. After 24 hours, the remaining slurry was vacuum filtered, the solution collected, and the solid washed with deionised water and dried in a 50°C oven overnight. All cyanide contaminated solutions and apparatus were treated with sodium hypochlorite to destroy any residual cyanide before being discarded.

**Acid Leach**

Sulfuric acid leaches were conducted in parallel on the same eighteen sample types utilising the standard bottle roll leaching procedure at ambient conditions over a 1 hour period with sampling of the slurry occurring at 15, 30 and 45 minute intervals. 25 g samples (P80 -100 µm) were placed into a 250 mL nalgene bottle along with 150 mL of 5% sulfuric acid, and rolled at a speed of 60 rpm on a bottle roller. After 1 hour, the remaining slurry was vacuum filtered, the solution collected, and the solid washed with deionised water and dried at room temperature.

**Analysis**

Solution samples from the cyanide and acid leaches were analysed for Au and Cu and Cu and Fe, respectively, using atomic absorption spectroscopy (AAS, Varian SpectrAA-800). Al, Ag, As, Bi, Co, Cd, Cr, Fe, Mg, Mo, Mn, Ni, Pb, Se, Te, Zn and W concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP-OES, Varian VISTA-PRO) and inductively coupled plasma mass spectrometry (ICP-MS, ALPH 3125). For the cyanide leaches, the concentrations of thiocyanate (SCN⁻) and thiosulfate (S₂O₃²⁻) were determined by high performance liquid chromatography (HPLC) on a Waters 2695 HPLC instrument.**

**RESULTS AND DISCUSSION**

For the purpose of this paper, “percent recovery” is defined as the mass of element leached as a percentage of its original mass within the ore sample. “Percent leached” is defined as the mass of element leached as a percentage of total ore sample mass. In this preliminary investigation, gold and copper head sample concentrations were obtained from MLA data. An improved quantitative indication of gold recovery could be obtained by conducting fire assays on head and tails samples.

**Gold Recovery**

Gold recoveries from cyanide leaching varied significantly across the samples from this gold ore site and ranged from 9–100%. This indicates a variability in the refractory nature of gold in the deposit. Cyanide leaching at ambient temperature and pressure may therefore not be economically feasible as a processing option for this site, with further treatment processes required to optimise gold extraction. Pre-treatment processes such as roasting, pressure oxidation, pre-oxidation and...
ultrafine grinding may unlock the non-refractory and mildly refractory minerals (<80% recoveries)\(^{(7)}\), however, the cost effectiveness of this option would need to be evaluated. Most of the gold dissolution occurred within the first 1.5 hours of the leach, with a reduction in leaching rate and steady state being reached after approximately 6 hours, as shown for three representative samples in Figure 1. Gold dissolution is not expected to occur in the acid leach, however, a small amount of acid soluble gold was found in the samples, with recoveries varying from 0.9 to 10.5%.

![Figure 1: Typical Gold Recovery Profiles in Cyanide Solution for Three Representative Samples from the Eighteen Samples Leached (25 g Sample, 1.5 g/L Sodium Cyanide Solution, 24 hours, Room Temperature)](image1)

The gold mineralogical deportment (provided by the site in the form of MLA data) was used to further explain the cyanide and acid leach recoveries and variability in gold recovery. All free gold present in the samples would be expected to leach completely in a cyanide solution, as it is directly accessible to undergo cyanidation. As expected, the recovered gold is equal to or greater than the amount of free gold present in the ore (with the exception of sample 2) as the amount of free gold in the samples is expected to be limited (Figure 2). The lower than expected gold leach recovery of sample 2 could be from the formation of an inhibiting surface layer which slows dissolution, however, this has not been confirmed and further investigation is required to explain this behaviour. Note: gold deportment data may display inaccuracies owing to inadequate representivity as a result of the scattered nature of gold within most deposits and the particular sample size used. A sample mass of 25 g would be representative for gold if all material were less than 60 \(\mu m\)\(^{(10)}\). In these tests, material less than 100 \(\mu m\) was used to produce a final leach residue of a sufficiently coarse size for QEMSCAN analysis. Unfortunately, this increases experimental error and fluctuations around the data. However, the primary aim of this study was not to determine absolute gold recoveries but rather to highlight trends and the additional information that can be obtained from the leaches.

![Figure 2: Comparison of the Free Gold Percentage in the Ore Samples vs. the Gold Leached in Cyanide Solution (25 g Sample, 1.5 g/L Sodium Cyanide Solution, 24 Hours, Room Temperature)](image2)

Figure 3 shows that the total gold leached does not equate to the amount of gold present in the samples. Gold present in refractory minerals, such as the silicates, plagioclase and tellurides\(^{(11)}\), will only leach partially in solution, and to some extent depending on crystal structure e.g. pyrite\(^{(7)}\). The gold associated with pyrite and the degree of gold liberation is somewhat responsible for the
refractory nature of the ore, as the two samples with 100% gold-pyrite association (samples 6 and 11) yielded recoveries of only 33 and 70%, indicating some gold associated with pyrite is leachable while some is locked within the mineral and does not leach. Some samples also contain significant amounts of gold associated with quartz. Any gold locked within quartz veins will not leach in cyanide solution without some form of pre-treatment, as seen from the small amount of gold leached in samples 2 and 10 where the gold is associated with quartz and quartz, silicates and pyrite, respectively. QEMSCAN analysis was performed on the leach residues and it was found that silicates such as potassium feldspar and plagioclase feldspar and pyrite were leached partially in both the cyanide and acid leaches, despite the low acid concentration. They were also leached to the same extent, suggesting that the same silicates and sulfides were leached in both the acid and cyanide leaches. There is no correlation between the cyanide soluble gold and the acid soluble gold; which could suggest that the free surface gold is not soluble in an acid leach, whereas the gold associated with the leached silicates is. However this has not been proven and further study is required. Note: the total gold reported from MLA analysis does not always equal 100% as some of the gold-containing minerals cannot be specified and are reported as “other”.

![Gold Leached in Cyanide Leach Compared with Total Gold Present from the Gold-containing Minerals in each Sample](image)

In summary, the high mineral variability in the samples and refractory nature of some of the gold-containing minerals results in high variability in gold recoveries. Possible pre-treatment options may need to be considered when determining the viability of gold extraction from this deposit.

**Copper Analysis**

Many porphyry gold deposits are known to contain substantial proportions of copper minerals in the form of sulfides and oxides. The presence of these soluble copper minerals in gold ores is probably the most frequent interference source during cyanidation. A copper content of less than 0.01% can still affect gold dissolution significantly, owing to the fact that copper minerals are readily dissolved in cyanide solutions and can cause excess reagent consumption.

Investigations performed by Hedley and Kentro\(^{12}\) and Hedley and Tabachnick\(^{13}\) provided the solubility of various copper oxide and sulfide minerals in sulfuric acid and sodium cyanide solutions\(^{14}\). These solubilities are listed in Appendix 1 and provide a basis for the predicted copper recoveries throughout this analysis. Mineralogical analysis showed that the predominant copper mineral in the samples is chalcopyrite (CuFeS\(_2\)). It is therefore expected that an approximately 1:3 mass ratio exists between the copper and chalcopyrite based on the stoichiometric formula (63.5 g/mol Cu:183 g/mol CuFeS\(_2\)= 0.3447). There is some variability around the approximate 1:3 correlation of copper and chalcopyrite in Figure 4 (with a 98.56% probability that the two data sets are related, see Table 1). This may occur because of the limited representivity in sampling being amplified for the low chalcopyrite grade samples (see circled values in Figure 4) or because the stoichiometry of copper within the sample may not always be 100% owing to effects such as weathering. However, the fact that the copper to chalcopyrite ratio is higher than 1:3 for many samples may indicate that minor amounts of other soluble copper minerals, not detectable by MLA, are present in the samples.
According to Appendix 1, chalcopyrite should only leach up to 2 and 7% in sulfuric acid and cyanide solutions, respectively, however, both the acid and cyanide leached on average 50 and 30% more copper, respectively, than expected (see typical cyanide and acid recovery profiles in Figures 5 (a) and (b), respectively). Studies into the kinetics of chalcopyrite dissolution in cyanide solution\(^{(15)}\) indicate that copper recovery increases relatively linearly with time. The copper in these samples is extracted rapidly initially (Figure 5 (a)) before the graph levels off. This again highlights the fact that it is possible that there are additional copper minerals not visible from mineralogical data that contribute to the copper recovery in the early stages of leaching. This indicates that predicting copper leaching based on mineralogy alone can produce underestimations of nuisance copper recoveries during leaching.

Further correlations were explored in Table 1 to investigate the dissolution of copper in the ore samples. A positive correlation was found to exist between the copper leaching in cyanide and the percentage chalcopyrite in the ore. Lastly, a strong correlation was found between the copper recovered in cyanide and the copper recovered in acid, which is to be expected since it is known that the same copper minerals will leach in each reagent but to differing degrees.

### Table 1: Summary of Copper Correlations

<table>
<thead>
<tr>
<th>Correlation</th>
<th>R(^2)</th>
<th>t</th>
<th>P(t)</th>
<th>Correlation type</th>
<th>Confidence interval (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu in head assay (%) vs. chalcopyrite (%)</td>
<td>0.3378</td>
<td>2.77</td>
<td>0.0144</td>
<td>Positive</td>
<td>98.56</td>
</tr>
<tr>
<td>Cu leaching in cyanide (ppm) vs. chalcopyrite (%)</td>
<td>0.2619</td>
<td>2.31</td>
<td>0.0357</td>
<td>Positive</td>
<td>96.43</td>
</tr>
<tr>
<td>Cu recovery in cyanide (%) vs. Cu recovery in acid (%)</td>
<td>0.4385</td>
<td>3.42</td>
<td>0.0038</td>
<td>Positive</td>
<td>99.62</td>
</tr>
</tbody>
</table>

### Sulfur Species Formation

According to Kenneth\(^{(16)}\) and Breuer\(^{(15)}\), free cyanide can react with sulfides or thiosulfate in solution to form thiocyanate according to Eqs (4) and (6) below. (It should be noted that thiosulfate can also be oxidised to sulfate.) The thiosulfate species form from sulfide mineral dissolution in cyanide solution, an example of which is given for chalcopyrite in Eq. (5).
From literature, the main minerals contributing to thiocyanate formation are chalcopyrite, chalcocite, pyrrhotite and free sulfur, with iron sulfides such as pyrite having an insignificant impact. Of these minerals, chalcopyrite and pyrrhotite were found to contribute to thiocyanate formation in this ore with p-values of $2.95 \times 10^{-3}$ and $7.83 \times 10^{-6}$, respectively. This agrees with the mineralogical data that shows that chalcopyrite and pyrrhotite are the main copper and iron sulfide minerals in the ore samples, respectively.

A correlation of SCN/Cu mole ratio versus rock type was found to exist in samples from previous test work. Figure 6 shows the molar ratio of thiocyanate to copper in solution (to normalise the data for sulfide produced by the leaching of chalcopyrite) plotted against the percentage pyrrhotite in each sample. The two circled outliers in Figure 6 can be removed with greater than 95% confidence through application of the Grubbs test (Appendix 2). Pyrrhotite dissolution consumes cyanide via Eq. (4) with the two samples with highest reagent consumption also having the highest pyrrhotite content. For additional samples, if the SCN and Cu solution concentrations were known, the SCN/Cu ratio could potentially be used as a predictor of pyrrhotite or sulfide content (and thus potential cyanide consumers) for the samples without additional mineralogical analysis, as chalcopyrite and pyrrhotite are the predominant sulfide minerals in the samples.

![Figure 6: Correlation between the Thiocyanate:Copper Ratio and Percentage Pyrrhotite of Each Sample](image)

Sulfur species formation depends on the relative extents of reaction according to Eqs (4) to (6). A gradual decrease in thiosulfate concentration occurs in the leach solutions between six and 24 hours for eleven of the eighteen samples (Figure 7) with typical thiosulfate/thiocyanate concentration profiles for two of these samples shown in Figure 8. Thiocyanate and thiosulfate are both generated from sulfide mineral oxidation (Eqs (4) and (5)). Thiosulfate can also react with cyanide according to Eq. (6) although the kinetics of this reaction are slow. For these samples, the thiocyanate concentration continues to rise, suggesting that some sulfide species are still being oxidised. The decrease in thiosulfate concentration indicates that the reaction of cyanide with thiosulfate is greater than the thiosulfate formation from mineral oxidation. The seven samples where thiosulfate production continues to increase with time have high total sulfur contents, suggesting thiosulfate continues forming from sulfide mineral oxidation in solution according to Eq. (5).
Reagent Consumption

Excess reagent was supplied to ensure conditions were not limiting and reagent requirements have not been optimised in these tests. The reagent concentrations remained above the accepted critical threshold limits during the leaches and sufficient reagent was present for all leaches to go to completion. The available acid and cyanide concentrations dropped on average by 3.6 and 30%, respectively. Figure 9 shows the theoretical cyanide consumption by those elements or species in solution that could form cyanide complexes (Ni, Ag, Co, Au, Fe and Cu), as well as thiocyanate (SCN) and the actual cyanide consumed (NaCN), assuming 4, 2, 6, 2, 6 and 3.5 cyanide ions per metal cyano-complex respectively. The main contributors to cyanide consumption were copper- and iron-forming cyanide complexes and from thiocyanate formation in solution. The unaccounted-for amount of cyanide consumption is assumed to result from experimental conditions or volatilisation and differs for each sample.
Trace Element Recovery

If trace elements present within the gangue minerals dissolve during the leaches, they may pose a toxic threat to the environment or present difficulties in removal in downstream separation processes. A set of trace elements (Ag, As, Bi, Cd, Co, Cr, Fe, Mn, Pb, Sn, Te, W and Zn) were monitored during the cyanide and acid leaches to predict the dissolution of gangue minerals. These were found to display a large degree of variability. Of the trace elements monitored, As, Cr, Bi, Te and Al were investigated further, as the solution concentrations of these elements after leaching were above the Australian guideline limits for wastewater disposal.

Trace element solution concentrations from sulfuric acid leaches were higher than those from cyanide leaches, with the exception of iron. This could pose problems if the formation of acid drainage were to occur within the tailings disposal facility.

Arsenic concentrations of up to 0.79 mg/L were found in both leach solutions. Despite mineralogical analysis indicating that arsenic is contained in arsenopyrite, no correlation was found between the amount of arsenic and arsenopyrite in each sample (Table 2) suggesting that arsenic is present in other mineral(s) not indicated by mineralogical analysis alone. Arsenic may also be present in other low abundance minerals that cannot be identified by mineralogy. A strong correlation was found to exist between the arsenic recovered in the cyanide and acid leaches, suggesting the same mineral(s) was leaching but to different extents. The cyanide leached 15–66% of the arsenic leached by the sulfuric acid, suggesting the arsenic is present in more acid- than cyanide-soluble minerals. Arsenic leached from the sulfuric acid leach was found to exceed the United States Environmental Protection Agency guidelines of 0.5 mg/L\(^{(19)}\), which could cause problems if the formation of acid drainage occurs. Therefore waste solutions and solids would need to be processed further before disposal to comply with the guidelines.

<table>
<thead>
<tr>
<th>Table 2: Trace Metal Correlations</th>
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<tr>
<td><strong>R^2</strong></td>
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<tr>
<td>As in ore (%) vs. arsenopyrite (%)</td>
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<tr>
<td>Recovery of As in acid (%) vs. cyanide (ppm)</td>
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<tr>
<td>Cr (%) vs. Al (%)</td>
</tr>
<tr>
<td>Bi (%) vs. Te (%)</td>
</tr>
<tr>
<td>Al (%) vs. Ca (%)</td>
</tr>
<tr>
<td>Al and Ca (%) vs. calcite (ppm)</td>
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</table>

The chromium leached during the acid leach was found to be above the 20 mg/L guideline for industrial wastewater disposal for two of the 18 samples\(^{(20)}\). There was a correlation between the aluminium leached and the chromium (Table 2), however, no correlation was found between these two elements and any of the minerals detailed in the mineralogy. This suggests that knowledge of the mineralogy is insufficient to determine which trace elements are recovered in the acid and cyanide leaches.

Limited information is available on the environmental toxicity impacts of bismuth and tellurium and regulations on their disposal limits change depending on application. A correlation existed between both elements (Table 2), except for one sample, which was found to contain significantly more muscovite than the other samples. The reason for the impact of high muscovite content is unknown. A correlation between bismuth and tellurium and possible mineral sources could not be found, again suggesting that it is not possible to determine from which minerals trace elements are being leached. There is the possibility that these elements substitute and replace naturally occurring elements in other minerals.

The Agriculture & Resource Management Council of Australia and New Zealand\(^{(20)}\) states that the accepted levels of aluminium in wastewater is 100 mg/L since aluminium compounds can precipitate as scale that can affect or block pipes, in the presence of calcium. The final aluminium levels in leach solutions ranged from 105 to 344 mg/L. Calcium concentrations ranged from 253 to 892 mg/L. It was found that there was a correlation between the amount of aluminium plus calcium leached and the amount of calcite in the samples, which accounts for the calcium leaching from the samples. However, it should be noted that this is not the source of the aluminium, which is likely to be from silicates such as feldspar and plagioclase.
Trace element concentrations as determined from leach solutions therefore indicate that mineralogical analysis is insufficient for predicting trace element deportment during leaching.

CONCLUSIONS

The large variability in gold recoveries reflects the variation in refractory nature of the ore samples investigated. Findings suggest that pre-treatment should be introduced before cyanide leaching to make the deposit economically viable, since most samples reflect a moderately refractory ore with gold recoveries of between 50 and 80%. It was expected that all free gold would leach completely and indeed this was found to be the case with one exception. The gold leached is less than the total gold present in the samples. This occurs because the gold is present in minerals with low solubility in cyanide, such as quartz, or as fine-grained inclusions in pyrite or may be locked.

Chalcopyrite was predicted to be the predominant copper mineral in the samples from mineralogical analysis and nuisance copper dissolution is expected to occur mainly from chalcopyrite. However, a plot of copper versus chalcopyrite content yielded a percent mass ratio larger than 0.3447 indicating that other minor amounts of soluble copper minerals, not detectable by MLA, may be present in the samples. This is further indicated by a plot of the recovery kinetics where the initial rapid dissolution of copper is most likely not from chalcopyrite alone in the early stages of leaching. Predicting copper recoveries from mineralogy alone could produce underestimations of nuisance copper recoveries during leaching.

Chalcopyrite and pyrrhotite were found to contribute to the formation of thiocyanate in cyanide leaching solutions. It was also found that the determination of SCN/Cu from solution may allow for the prediction of pyrrhotite (or sulfide) content. The formation of thiocyanate and thiosulfate species is complex and again cannot be predicted from mineralogy. Determination of sulfur species from leach solutions could assist in the management of cyanide species and cyanide destruction and recovery processes. Copper and iron (most likely from chalcopyrite and pyrrhotite) were the main contributors to cyanide consumption.

Undesirable trace elements are leached to a greater extent in sulfuric acid than cyanide solution, suggesting that these elements are contained in acid soluble minerals that would be susceptible to leaching if acid drainage were to occur thereby possibly causing environmental problems. A number of leach solutions contained arsenic with concentrations exceeding environmental concentration limits, therefore additional processes for the removal of arsenic from solution before disposal would have to be considered. The percentage of trace elements such as chromium, bismuth and tellurium leached into solution cannot be determined from mineralogy alone, therefore leaches must be performed to determine which elements may pose environmental or downstream difficulties.

Overall, diagnostic leaching is a potential tool for predicting the recoveries of selected elements and their mineralogical associations, as well as reagent consumption, speciation and the dissolution of trace elements in gangue minerals. The latter two elements are obtained in addition to what is usually derived from traditional industrial diagnostic leaches and may be of great benefit for reducing reagent costs and ensuring compliance with health and safety regulations.
REFERENCES


