



Neutralization of bioleach liquors

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Synopsis

Mintek has been involved in the development of bioleach technology for many years, initially for refractory gold extraction, and more recently also for base metals extraction. Mintek, in collaboration with its Australian technology partner (BacTech), is the technology provider for the Beaconsfield refractory gold bioleach plant. At present Mintek, BacTech and Peñoles are constructing a demonstration bioleach plant for copper-zinc concentrate treatment. Bioleach liquors produced in all applications have to be neutralized. In the copper-zinc case, neutralization is required for bleeding iron from the circuit and for adjusting the pH value ahead of solvent extraction. In the refractory gold bioleach circuit, neutralization is required for producing a stable iron-arsenic residue.

Some of the challenges encountered in each of these neutralization applications are discussed, and examples of results obtained are presented.

Introduction

In both the copper-zinc and the refractory gold bioleach processes developed at Mintek, iron and arsenic are common impurities produced that need control. Besides the need to prevent impurity build-up, these species need to be rejected in an environmentally friendly form.

The production of stable iron-arsenic precipitates by neutralization, to meet the environmental requirements, has been well publicized. In the copper-zinc process, neutralization is not only employed for bleeding iron from the circuit, but also for pH adjustment of the solvent extraction (SX) feed.

The conditions and the manner under which the neutralization process is operated can vary, depending on the requirements of downstream unit operations. This paper deals with the neutralization challenges encountered with respect to both base metals and refractory gold bioleaching, respectively.

Neutralization stage challenges: base metal applications

Design criteria

The following requirements should be met

during the neutralization of copper-zinc bioleach liquor:

- ▶ The neutralization plant must produce a product with good settleability, filterability and dewatering characteristics, to minimize the size of the solid-liquid separation plant, and to minimize the need for wash water that dilutes the bioleach liquor
- ▶ Co-precipitation of the valuable metals in the precipitate should be avoided
- ▶ The utilization of the neutralizing agent (typically CaCO_3) should be maximized.

Impact on the process

Figure 1 shows a simplified block flow diagram of the copper-zinc bioleach process, consisting of the leach step followed by solid-liquid separation. The bioleach liquor is neutralized, and the liquor is decanted from the resulting neutralization product sludge, using a settler. The settler underflow is filtered and washed, with the filtrate being returned to the settler. The decanted liquor is clarified ahead of solvent extraction, and most of the solvent-extraction raffinate is recycled to the leach step. A portion of the raffinate may need to be bled, for example for the purpose of zinc recovery.

In the neutralization step, limestone is typically used to raise the pH level, to neutralize free acid, and to precipitate ferric iron in the form of ferric hydroxide. Gypsum also forms in the process, which provides a matrix for crystal growth and improves the settling and filtration characteristics of the neutralization product.

As an example to illustrate the impact that the neutralization step can have on the overall process, consider the treatment of 1 000

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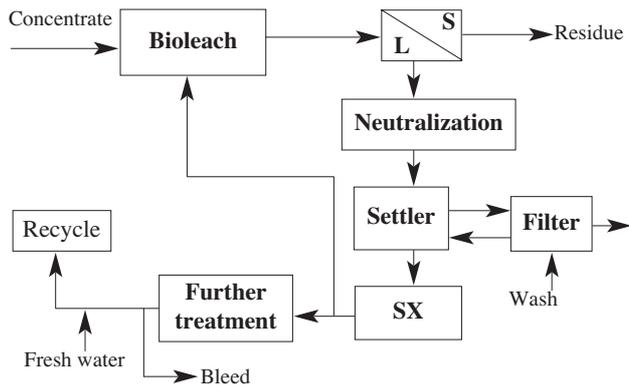
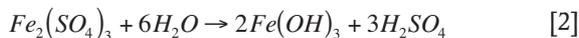


Figure 1—A simplified copper-zinc bioleach block flow diagram

kg/day of chalcopirytic concentrate, containing 27 per cent copper, 30 per cent iron, and 5 per cent quartz, with the balance being inert. It will be assumed that minimal iron precipitation occurs in the leach step, since the bioleach residue will often contain precious or other valuable metals for downstream recovery, for which purpose it is important not to dilute the residue with precipitates.

There are two important neutralization reactions. Sulphuric acid is neutralized to produce gypsum, and ferric sulphate is hydrolysed to form ferric hydroxide and sulphuric acid. Assuming CaCO_3 is the neutralizing agent, the reactions are as follows:



From simple stoichiometric calculations, the neutralization product in the above example is estimated to consist of about 500 kg of $\text{Fe}(\text{OH})_3$ and 1 300 kg of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

The neutralization product therefore constitutes the largest flow of solids in the flowsheet. The relative size of this residue makes the limitation of its copper content, to prevent copper losses, of the utmost importance. In order to achieve this, it should be ensured that the neutralization product solids are crystalline, which depends on operation of the neutralization plant under optimal conditions.

Furthermore, the neutralization product should have good filtration and dewatering characteristics, since the need for a high filter cake wash ratio will lead to unacceptable dilution of the neutralized liquor (i.e. the solvent-extraction feed liquor).

The challenge

When bioleach liquor is simply neutralized by the direct addition of limestone slurry at ambient or near-ambient temperature, it is found that none of the design criteria discussed above is met. Owing to the formation of a largely amorphous product, the solid-liquid separation characteristics of the neutralization precipitate thus formed, and the utilization of neutralizing agent under these conditions, can be poor enough to be totally unsuitable for large-scale implementation. The loss of copper to such precipitates is also unacceptable, and amorphous precipitates formed by direct neutralization to a pH level of about 2.5 have been found to contain both un-neutralized acid and un-utilized

limestone. These problems can largely be overcome by performing the neutralization step above 70°C. However, that in turn can require a large heat input, especially if the leach step is performed at a 'low' temperature (below 70°C).

Bioleach feed stocks of different mineralogy require different combinations of leach conditions, including different optimal temperature ranges. Therefore, if large heating (and subsequent cooling ahead of solvent extraction) duties are to be avoided, a neutralization system which can operate successfully over a wide range of temperatures is ideally required, including the 'low' temperature range to cater for moderately thermophilic and mesophilic bioleach systems.

The approach adopted to devise a neutralization system operating at 'low' temperature, was to apply the principles of crystallization, to ensure a crystalline gypsum-ferric-hydroxide product. A system for the 'low' temperature production of crystalline neutralization product was firstly devised and tested using a series of batch tests, and was then implemented in a mini-scale continuously operated system, consisting of four one-litre reactors connected in series (allowing gravity flow between reactors) and a settler. The pH values in the reactors could be maintained either by manual manipulation of the reactor feed flow rate, or by the use of a system of pumps and controllers. Furthermore, the benefit of larger-scale experience on other water treatment applications has been available for the practical engineering of this step.

Practical design example

The optimal conditions and plant configuration of a 'low' temperature neutralization step were determined for a bioleach demonstration plant, being constructed in Mexico.

It has been possible to define a set of neutralization plant operating conditions which satisfy all the desired criteria, the most important of which are summarized in Table 1.

These results were obtained in small-scale experimental equipment. It is expected that a lower filter cake moisture content can be achieved in an industrial pressure filter.

Summary and conclusions: Base metals

The functions of the neutralization step in base metals bioleaching are:

- Removal of iron from the circuit
- Adjustment of the pH value of the solvent extraction feed liquor.

Table 1

Base metals bioleach neutralization plant performance

Parameter	Value
Settler underflow solids content	30–40%
Filter cake moisture content	29%
Filter cake wash ratio	2 l/kg solids (dry basis)
Copper loss by co-precipitation	Undetectable (<0.3% of copper extraction)
Utilization of neutralization agent	90%
Dilution of bioleach liquor over neutralization step	20%

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Important design criteria for the neutralization step are:

- ▶ Production of a neutralization product with good solid-liquid separation characteristics
- ▶ Minimization of the co-precipitation of valuable metals
- ▶ Maximum utilization of the neutralizing agent.

Because the neutralization product can constitute a relatively large solids stream, a lot of potential exists for high copper losses by co-precipitation if co-precipitation is not minimized. Furthermore, the need for a high filter cake wash ratio will result in undue dilution of the solvent-extraction feed liquor.

Direct neutralization of bioleach liquor with limestone slurry does not meet any of the design criteria if the neutralization is conducted at 'low' temperatures (below 70°C). However, by utilizing the principles of crystallization, a system has been devised whereby a crystalline gypsum-ferric-hydroxide product is formed at 'low' temperature.

From a series of batch tests, followed by small-scale continuous tests, and by drawing on existing expertise on larger-scale water treatment applications, it has been possible to design a 'low' temperature neutralization section for a demonstration plant, being erected in Mexico, which meets all the required design criteria.

Refractory gold applications

Background

In a refractory gold bioleach process, the main constituents of the leach liquor are typically iron, arsenic, and sulphuric acid (H₂SO₄). The iron is usually present in the ferric (Fe³⁺) state, as ferric sulphate (Fe₂(SO₄)₃), and the arsenic is usually present in the arsenate (As⁵⁺) state, as arsenic acid (H₃AsO₄). The primary objective of the neutralization step is to neutralize the acid, and to precipitate the iron and arsenic in a stable form suitable for safe disposal. Clearly, the presence of arsenic in the precipitate would be a cause of concern if there was any chance of re-mobilization of the arsenic into the environment.

Current industrial practice

Figure 2 shows a typical block flow diagram for the refractory gold bioleach process.

As illustrated, there is the possibility of settling (or even filtering) the neutralized product, in order to recover water. If this was the case, then the process would need to produce a

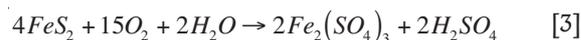
product with good settling or filtration characteristics.

Furthermore, if the feed material was a bulk concentrate derived from a gold- and copper-bearing ore, the bioleach liquor may contain copper at a concentration that would warrant its recovery. In this case, co-precipitation of copper in the neutralization process would need to be avoided.

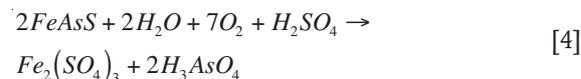
Current practice in commercial bioleach plants is to neutralize with limestone in a four-stage process under ambient temperature conditions. For example, at the Beaconsfield bioleach plant in Tasmania, limestone is added to the first and third neutralization tanks. The pH value is increased to 3.0 in the first stage, and then further increased to around 6.5 in the third stage. The neutralization tanks are aerated, the process is conducted at ambient temperature, and the overall residence time is six hours. Interestingly, water is recovered after neutralization. The entire neutralized product is combined with the flotation tailing, and then thickened. The thickened solids are dispatched to the tailings facility, and the water is re-used.

Chemistry of oxidation and neutralization

The bacterial oxidation of pyrite produces ferric sulphate and sulphuric acid, as follows:



The bacterial oxidation of arsenopyrite produces ferric sulphate and arsenic acid, as follows:



The neutralization by limestone of the sulphuric acid present in a bioleach liquor proceeds according to reaction [1], to produce gypsum.

Controversy has raged over the composition of the amorphous precipitates that are formed when iron- and arsenic-bearing liquors are neutralized with limestone at ambient temperature. Some investigators^{9,10} have suggested that 'basic ferric arsenate', $FeAsO_4 \cdot xFe(OH)_3$, is formed, while others¹⁴⁻¹⁷ have disputed this and proposed that the product is in fact arsenate absorbed onto extremely small particles of ferric hydroxide.

Assuming that the formula proposed for the production of 'basic ferric arsenate' is correct, it can be postulated that the precipitation of a bioliquor containing iron and arsenic in a molar ratio of $x+1:1$ proceeds as follows:

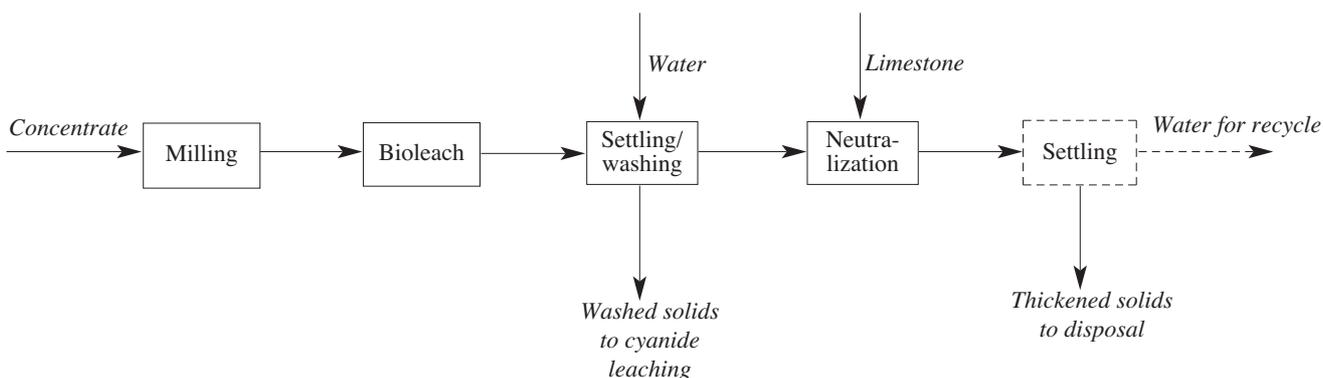
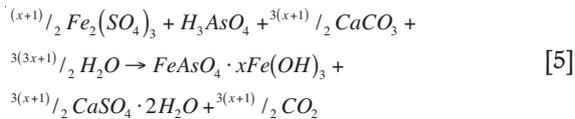


Figure 2—A simplified refractory gold bioleach block flow diagram

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Equations [1] and [5] can be used to estimate the limestone requirements for the neutralization of a bioleach liquor, and to estimate the quantity of precipitated solids that will be produced in the process.

Factors affecting arsenic stability

A number of factors have been found to affect the stability of iron-arsenic precipitates. Broadly speaking, the following factors have been found to influence the arsenic stability of these materials^{3,7,9,10,13,15,20}.

- ▶ Precipitation should be conducted in stages, with a gradual increase in the pH level, in order to avoid the formation of calcium arsenate, $Ca_3(AsO_4)_2$, which is not a stable product.
- ▶ The neutralization process should be conducted in the presence of air, to ensure that oxidizing conditions are present. This has a beneficial effect on the efficiency of iron and arsenic removal during the neutralization process.
- ▶ The molar iron-to-arsenic ratio in the bioleach liquor is a crucial factor in ensuring that the product is stable. The higher the iron-to-arsenic ratio, the more stable is the resulting precipitate. It is generally considered that a liquor with a molar iron-to-arsenic ratio of at least 3:1 is required to produce a precipitate that is suitable for disposal.
- ▶ The temperature of the process—at least at temperatures between 25 and 80°C—does not significantly affect the stability of the resultant precipitate.
- ▶ The presence of base metals (such as zinc, copper, and cadmium) and of gypsum has the effect of enhancing the stability of iron-arsenic precipitates.
- ▶ The pH level at which the precipitate is stored is also an important factor. Typically, iron-arsenic precipitates are most stable at a pH level of between 4 and 5.
- ▶ The effect of, for example, an increased iron-to-arsenic ratio, and the presence of base metals or gypsum, is to extend the pH range within which the resulting precipitate is stable.

Stability testing

Short- and long-term procedures

The most commonly-used method to determine stability of metallurgical wastes is the United States Environmental Protection Agency Toxicity Characteristic Leaching Procedure (U.S. EPA-TCLP), which is a short-term procedure, conducted at a single pH level using acetic acid over a period of 18 hours²². However, the applicability of this procedure, and other similar procedures in use in various parts of the world, has been questioned by several investigators^{4,5,8,16}. The procedures suffer from many important shortcomings, the most obvious of which are that they do not provide an indication of long-term stability, and that they do not model the conditions typically found in the disposal site. Despite this, they are widely used by investigators wishing to establish the suitability of waste materials for disposal.

Of course, a short-term test does have some value in that a material that displays stability in the short term may well do so in the long term. Clearly, a material that displays short-term instability should probably not be considered for disposal. Alternatively, short-term stability tests can be used to screen waste materials, and a material that passes a short-term stability test could then be considered to be a candidate for a longer-term test.

Neutralization and stability test work

In order to evaluate the stability of iron-arsenic waste materials in the long term, several long-term stability tests were conducted on neutralized precipitates from two bioleach liquors. The first bioleach liquor was characterized by having a relatively low iron-to-arsenic ratio, whereas the second had a very high iron-to-arsenic ratio. The iron and arsenic analyses of the two liquor samples are shown in Table II.

These bioleach liquors were neutralized in a semi-continuous procedure^{9,10} using slaked lime ($Ca(OH)_2$). During the neutralization, the slurry was aerated, the pH was controlled at a level of around 5, and the temperature was maintained at between 19 and 26°C. The resulting precipitate was subjected to a three-stage water wash.

The washed solids which passed a U.S. EPA-TCLP test, were then taken forward to the long-term stability test procedure^{9,10}. A sample of the washed precipitate was slurried at 10 g solids/l in a 500 ml Erlenmeyer flask using pH-adjusted deionized water. For each sample, four flasks at pH levels of 3, 5, 7, and 9 were set up. The slurry was agitated for about 10 minutes using a magnetic stirrer, the pH level was measured, and adjusted if necessary using either a 0.5 N H_2SO_4 solution or a 150 g/l $Ca(OH)_2$ slurry.

The flask was then covered with a watch-glass and the slurry allowed to settle for a period of 36 hours, after which a sample of supernatant was removed for arsenic analysis by ICP-MS. The rest of the supernatant was then decanted, ensuring that none of the solids was removed. The flask was then topped up to the original slurry mass using pH-adjusted deionized water. The contents of the flask were again agitated using the magnetic stirrer, the pH level adjusted if necessary, and allowed to stand for a few more days before the procedure of sampling, decantation, topping up, and pH adjustment was repeated.

These tests are designed to simulate the tailings dam environment, by using appropriate reagents (sulphuric acid and lime as opposed to acetic acid), by allowing for water flow through the tailings facility (by periodic decantation and topping up), and by allowing the solids to remain in a settled condition for the bulk of the time.

The tests were started in July 1993, and continue to be monitored to the present day—a period of 2 480 days, or

Table II
Composition of bioleach liquors

Component	Bioleach liquor 1	Bioleach liquor 2
Fe, g/l	33.6	55.6
As, g/l	14.3	1.4
Iron-to-arsenic ratio (mol/mol)	3.2	53.3

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almost seven years. The period between sampling has been increased with time, and sampling now occurs every few months.

The results of these long-term stability tests on the precipitates from Bioliquors 1 and 2 are illustrated in Figures 3 and 4, respectively.

Arsenic mobility—How much is acceptable?

In contemplating these results, the question must be asked—what is an acceptable arsenic level? Many guidelines and standards are encountered around the world.

- ▶ The World Health Organization has published^{5,6} a guideline for drinking-water quality, which allows a level of 0.05 mg/l.
- ▶ The permitted arsenic concentration in waste water in Japan is 0.5 mg/l²¹.
- ▶ In Brazil, the arsenic concentration limit is 0.2 mg/l^{1,2}
- ▶ In China, the regulatory requirement is an arsenic concentration of 0.5 mg/l¹¹.
- ▶ In British Columbia, Canada, an arsenic concentration of 1.0 mg/l may be discharged to fresh water.
- ▶ In Great Britain, the Department of the Environment allows co-deposition of arsenical wastes with landfill to release up to 10 mg/l of arsenic in leachate, and up to 25 mg/l when leachate is contained at hydrogeologically secure sites with no risk of groundwater contamination⁴.
- ▶ It has been suggested¹⁹ that waste solids which result

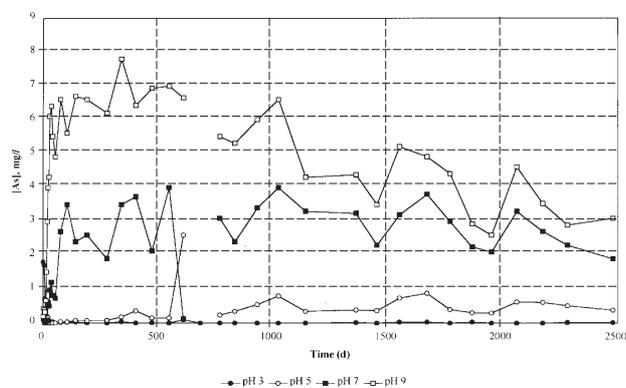


Figure 3—Long-term stability of Bioliquor 1 precipitate

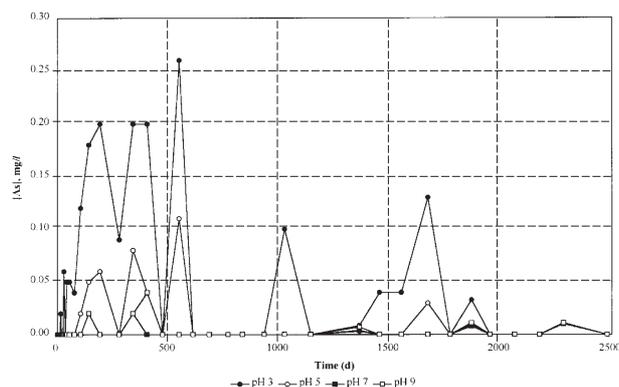


Figure 4—Long-term stability of Bioliquor 2 precipitate

in equilibrium arsenic levels of less than 10 mg/l would be acceptable to the Western Australian Environmental Protection Agency.

- ▶ For the short-term U.S. EPA-TCLP test, the threshold extract arsenic concentration is 5 mg/l.
- ▶ However, in Ontario, Canada, a similar short-term method is used to determine the stability of waste materials, and the arsenic threshold concentration is 0.05 mg/l¹².
- ▶ In British Columbia, Canada, a short-term procedure is also used, and the threshold arsenic concentration is 5.0 mg/l.
- ▶ In South Africa, effluents in water catchment areas are required to be below 0.1 mg/l of arsenic, whereas in less sensitive areas, a concentration of 0.5 mg/l is allowed¹⁸.

There is clearly little or no consensus on what constitutes an acceptable arsenic concentration. However, based on the range of requirements discussed here, it is apparent that a value of about 0.5 mg/l would be considered acceptable in most countries, while a value in excess of 5 mg/l would be unacceptable in most cases.

The results obtained for the Bioliquor 1 precipitate (Figure 3) clearly show the effect of the storage pH level on the stability of a precipitate with a molar iron-to-arsenic ratio of 3.2. As the pH level increases, the arsenic mobility increases. At a pH level of 3, almost no arsenic could be detected. At a pH level of 5, arsenic has continued to be mobilised at a level of between 0.5 and 1.0 mg/l. At a pH level of 7, arsenic concentrations are between 2 and 4 mg/l, and at a pH level of 9, arsenic concentrations of between 3 and 8 mg/l have been recorded, although the long-term trend is towards less mobility of arsenic. However, the results in the initial stages of this test (and to a lesser extent that conducted at a pH level of 7) showed a rapidly increasing level of arsenic instability, which peaked after around 400 to 500 days.

The striking feature of the results for the Bioliquor 2 precipitate (Figure 4) is that the arsenic mobility is far less than that for the Bioliquor 1 precipitate under all pH conditions. This result clearly shows the effect of the higher iron-to-arsenic ratio in the precipitate, which has conferred stability on the material. Interestingly, the precipitate stored at a pH level of 3 displayed some arsenic mobility in the first two years, and has occasionally shown some further mobility in the intervening period. However, a maximum arsenic concentration of 0.26 mg/l was measured. The precipitates stored at pH levels of 5 and 9 were also slightly unstable initially, but the long-term trend has been for an increase in stability, with arsenic virtually not being detected in most instances.

Implications and conclusions: refractory gold applications

This is the first time that the results of controlled long-term stability tests on iron- and arsenic-bearing precipitates derived from bioleach liquors have been published. The results presented here have several important implications.

- ▶ Most metallurgical tailings facilities are likely to be at pH levels above 7. Under these conditions, arsenic stability of precipitates with molar iron-to-arsenic

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ratios of around 3:1 cannot be guaranteed, and it is therefore recommended that a higher ratio should be targeted. Alternatively, for such applications, a separate tailings facility for the neutralized precipitate, where the pH could be maintained at a lower level, may need to be considered, but this is likely to result in additional costs. Finally, a different—and potentially more expensive—process may need to be contemplated for the neutralization plant.

- ▶ There is some evidence that, at the higher pH levels (7 and above), arsenic mobility can increase in the short to medium term, but that it then decreases over the longer term. Short-term stability tests would not have identified this behaviour.
- ▶ The fact that arsenic stability varies with pH level supports the argument that short-term tests are inappropriate, since they are usually conducted at a single pH value (typically 5).
- ▶ For all of the tests, the very long-term trend is for an improvement in arsenic stability. Precipitates that are stable initially tend to remain stable, and those that exhibit some instability in the first few years appear to gain in stability after about two years. This is a very encouraging finding, and indicates that fears that a decrease in stability could occur over the long term are unfounded.

The success of the continuous test work that has been performed at Mintek to establish parameters for the design of an iron-removal process for base metal bioleach applications will in the near future be used as a basis for improving the neutralization process for refractory gold applications. For example, a forthcoming project will evaluate the precipitation of both iron and arsenic from a bioleach liquor that contains copper in recoverable quantities. In this work, the objectives will be to produce a precipitate with good settling and filtration characteristics, to minimize limestone consumption, and at the same time to produce a suitably stable iron-arsenic precipitate.

References

1. CARTER, A.J. Economic comparison of the alternative methods for the recovery of gold from refractory gold ores. *Proceedings of the Colloquium on Bacterial Oxidation*, Johannesburg, South Africa, June 1991. SAIMM, 1991.
2. HAINES, A.K. and VAN ASWEGEN, P.C. Process and engineering challenges in the treatment of refractory gold ores. *Proceedings of the International Deep Mining Conference: Innovations in Metallurgical Plant*, vol. 1, Johannesburg, South Africa, 1990. SAIMM, 1990. pp. 103–110.
3. HARRIS, G.B., and MONETTE, S. The stability of arsenic-bearing residues. *Arsenic metallurgy: fundamentals and applications*. Reddy, R.G., Hendrix, J.L., and Queneau, P.B. (eds.). Warrendale, Pennsylvania, The Metallurgical Society, Inc., 1987. pp. 469–488.
4. HOPKIN, W. The problem of arsenic disposal in nonferrous metals extraction. *Arsenic metallurgy: fundamentals and applications*. Reddy, R.G., Hendrix, J.L., and Queneau, P.B. (eds.). Warrendale, Pennsylvania, The Metallurgical Society, Inc., 1987. pp. 363–384.
5. HOPKIN, W. Arsenic residue disposal in refractory gold treatment. *Proceedings of the Randol Gold Forum*, Cairns, Australia, April 1991. Golden, Colorado, Randol International Ltd., 1991. pp. 191–195.
6. KHOE, G.H. The stability of iron arsenate compounds. *Proceedings of the Randol Gold Forum*, Cairns, Australia, April 1991. Golden, Colorado, Randol International Ltd., 1991. pp. 185–189.
7. KONTOPOULOS, A., STEFANAKIS, M., and PAPANASSI, N. Arsenic control in hydrometallurgy by precipitation as ferric arsenates. *Proceedings of the 1st International Conference on Hydrometallurgy*, 1988. Yulian, Z., and Jiazhong, X. (eds.). Oxford, International Academic Publishers, 1988. pp. 672–677.
8. KRAUSE, E. Arsenic removal at Inco's CRED plant and disposal practice. Preprint from *EPA Arsenic and Mercury Workshop on Removal, Recovery, Treatment, and Disposal*, Alexandria, Virginia, August 1992. 5 pp.
9. KRAUSE, E. and ETTTEL, V.A. Ferric arsenate compounds: are they environmentally safe? Solubilities of basic ferric arsenates. *Proceedings of the Impurity Control and Disposal Symposium, 15th Annual Hydrometallurgy Meeting, 24th Annual CIM Conference*, Vancouver, Canada, August 1985. Paper 5. pp. 5–1—5–20.
10. KRAUSE, E., and ETTTEL, V.A. Solubilities and stabilities of ferric arsenate compounds. *Hydrometallurgy*, vol. 22. 1989. pp. 311–337.
11. MAOSUI, L. The purification of waste water with arsenic and fluoride contents. *Proceedings of the 1st International Conference on Hydrometallurgy*, 1988. Yulian, Z., and Jiazhong, X. (eds.). Oxford, International Academic Publishers, 1988. pp. 669–671.
12. Ontario Ministry of the Environment. Leachate extraction procedure. Ontario, the Ministry, *Regulation 309, Revised Regulations of Ontario, 1980*, under *Environmental Protection Act (General-Waste Management)*. January 1989.
13. PAPANASSI, N., STEFANAKIS, M., and KONTOPOULOS, A. Removal of arsenic from solutions by precipitation as ferric arsenates. *Arsenic metallurgy: fundamentals and applications*. Reddy, R.G., Hendrix, J.L., and Queneau, P.B. (eds.). Warrendale, Pennsylvania, The Metallurgical Society, Inc., 1987. pp. 321–334.
14. ROBINS, R.G. Arsenic hydrometallurgy. *Arsenic metallurgy: fundamentals and applications*. Reddy, R.G., Hendrix, J.L., and Queneau, P.B. (eds.). Warrendale, Pennsylvania, The Metallurgical Society, Inc., 1987. pp. 215–247.
15. ROBINS, R.G., HUANG, J.C.Y., NISHIMURA, T., and KHOE, G.H. The adsorption of arsenate ion by ferric hydroxide. *Arsenic metallurgy: fundamentals and applications*. Reddy, R.G., Hendrix, J.L., and Queneau, P.B. (eds.). Warrendale, Pennsylvania, The Metallurgical Society, Inc., 1987. pp. 99–112.
16. ROBINS, R.G. and JAYAWEEERA, L.D. Arsenic in gold processing. *Proceedings of the Randol Gold Forum*, Cairns, Australia, April 1991. Golden, Colorado, Randol International Ltd., 1991. pp. 171–178.
17. ROBINS, R.G. and JAYAWEEERA, L.D. Arsenic in gold processing. *Miner. Process. Extract. Metall. Rev.*, vol. 9. 1992. pp. 255–271.
18. South African Ministry of Environment Affairs and Fisheries. Requirements for the purification of waste water or effluent. Pretoria, South African Government, *Government Gazette*, no. 9225, notice no. 991. May 1984. pp. 12–17.
19. SPENCER, P.A. Critical parameters in bacterial oxidation: agitation, aeration, temperature & arsenic. *Proceedings of the Randol Gold Forum*, Squaw Valley, California, 1990. Golden, Colorado, Randol International Ltd., 1990. pp. 131–133.
20. STEFANAKIS, M. and KONTOPOULOS, A. Production of environmentally acceptable arsenites-arsenates from solid arsenic trioxide. *Arsenic metallurgy: fundamentals and applications*. Reddy, R.G., Hendrix, J.L., and Queneau, P.B. (eds.). Warrendale, Pennsylvania, The Metallurgical Society, Inc., 1987. pp. 287–304.
21. TOZAWA, K., NISHIMURA, T., and UMETSU, Y. Removal of arsenic from aqueous solutions. Paper presented at *16th Annual CIM Conference of Metallurgists*, Vancouver, Canada, August 1977. 11 pp.
22. United States Environmental Protection Agency. Proposed rules, part 261—identification and listing of hazardous waste. Washington, D.C., United States Government, *Federal Register*, vol. 51, no. 114. June 1986. pp. 21 685–21 692. ◆