INTRODUCTION

The treatment of refractory gold ores, in particular the competing technologies and their relative advantages and economics, has become a major issue for the industry and a topic of interest at conferences. A common theme is the increasingly refractory nature of gold ores being treated. Papers on refractory gold treatment have examined the characteristics of refractory ores and the causes of reduced recovery (La Brooy 1994), the available technologies and their relative economics (Litz 1990), and the selection of a suitable process route (Nicholson 1993, Weston 1994). The most comprehensive collation of data on such processes is provided in the various editions of Randol.

A variety of classifications and definitions of refractory ore has been published. Because of the many factors which can impact on the recovery of gold, it is not possible to develop a universal characterisation that can be applied to all gold-bearing rocks. La Brooy et al have provided a useful framework for characterisation as shown in Figure 1.

Figure 1
Gold Ore Characterisation

In this categorisation, ‘free milling’ ore is defined as having over 90% recovery under conventional cyanidation conditions, whilst those ores that give ‘acceptable’ economic gold recovery only with the use of significantly higher chemical (eg. cyanide, oxygen, carbon) additions are defined as ‘complex’. ‘Refractory’ ores are thus defined, by exception, as those which still give inadequate recovery. It is implicit in this definition that additional recovery requires some degree of pre-treatment prior to cyanidation. Any further characterisation of refractory ores, such as a definition of percentage recovery, is somewhat arbitrary and ignores the impact of economics unique to each specific ore deposit.

There are several reasons why ores display refractory characteristics. These include those shown in Table 1.
Table 1

Causes of Refractoriness

<table>
<thead>
<tr>
<th>Causes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liberation</td>
<td>Physical locking in silicates, sulphides, carbon etc.</td>
</tr>
<tr>
<td>Occlusion</td>
<td>Passivation due to formation of a chemical layer.</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Formation of auriferous compounds, eg. gold tellurides, aurostibnite</td>
</tr>
<tr>
<td>Substitution</td>
<td>Elemental replacement by gold in mineral lattice, eg. “solid solution” gold in pyritic ores.</td>
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</tbody>
</table>

Whilst these refractory characteristics can be seen in a variety of ore types, including auriferous base metals and rocks with a high carbon content, the major focus in refractory gold processing has been on gold-bearing iron sulphides, such as pyrite, arsenopyrite, pyrrhotite, telluride and the stibnite family. It is the intention of this paper to concentrate on the pretreatment processes available for the latter ore types.

REFRACTORY PROCESS ALTERNATIVES

The recent resurgence of the gold mining industries in areas such as North America and Australasia has focussed on free-milling oxide ores, largely due to the development of improved open pit mining and gold recovery techniques. With the recognition that many of these deposits continue at depth, but also turn more refractory, there has been significant interest in the development of improved techniques and processes for these more difficult ores. Much of this development has been driven by the need for more environmentally acceptable process routes and, in particular, the need to dispose of byproducts such as arsenic and sulphur in a responsible manner.

Table 2 lists some of the available processes which are either in industrial use or in advanced developmental stages.

Table 2

Refractory Process Routes

<table>
<thead>
<tr>
<th>Type</th>
<th>Industrial Processes</th>
<th>Developmental Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Whole ore roasting</td>
<td>Pyrolysis</td>
</tr>
<tr>
<td></td>
<td>Concentrate roasting</td>
<td>Flash roasting</td>
</tr>
<tr>
<td></td>
<td>Smelting</td>
<td></td>
</tr>
<tr>
<td>Oxidative</td>
<td>Acid pressure oxidation</td>
<td>Bio-heap leaching</td>
</tr>
<tr>
<td></td>
<td>Alkaline pressure oxidation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biological oxidation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nitric acid oxidation</td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>Hot caustic digestion</td>
<td>Ammonia leaching</td>
</tr>
<tr>
<td></td>
<td>Chlorine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressure cyanidation</td>
<td></td>
</tr>
<tr>
<td>Physical</td>
<td>Fine grinding</td>
<td>Ultrafine grinding</td>
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<tr>
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</tbody>
</table>
In some instances, it may even be appropriate to combine more than one of these processes in a synergistic manner, eg.

- ultrafine grinding prior to pressure oxidation (Activox®)
- hot caustic leaching of roaster calcines
- chlorination of carbonaceous oxidation products
- biological oxidation of pyrrhotite prior to pressure oxidation

**REFRACTORY PROCESS SELECTION**

In 1987, when Minproc undertook the feasibility study for the Bogosu project in Ghana, the only refractory processes considered to be in a suitable stage of development were pressure oxidation and concentrate roasting. Five years later, when evaluating the Sansu sulphide project for Ashanti Goldfields, it was necessary to undertake an extensive evaluation of a number of alternative processes. These included pressure oxidation, biological oxidation, concentrate roasting and the Freeport whole ore oxygen roasting process, as well as other options such as nitric acid oxidation and ultrafine grinding. The testwork programmes and engineering studies involved in this evaluation took over two years to complete at a cost of over US$2 M (Nicholson et al 1993).

Whilst it may not be necessary to undertake such a detailed programme for all refractory gold projects, it is certainly important not to make an arbitrary selection based on preconceived ideas of process attributes or on generic comparisons of process economics. In recent years, Minproc has been involved in the selection of refractory processes for the following projects and, in each instance, the process selection was based on factors unique to each project:

<table>
<thead>
<tr>
<th>Project</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogosu</td>
<td>Concentrate roasting</td>
</tr>
<tr>
<td>Sansu, Ashanti Goldfields</td>
<td>Concentrate BIOX®</td>
</tr>
<tr>
<td>Three Mile Hill</td>
<td>Concentrate fine milling</td>
</tr>
<tr>
<td>Macraes Flat</td>
<td>Concentrate fine milling/Pressure Oxidation</td>
</tr>
<tr>
<td>Kanowna Belle</td>
<td>Concentrate roasting</td>
</tr>
<tr>
<td>Minahasa</td>
<td>Whole ore roasting</td>
</tr>
<tr>
<td>Bakyrchik</td>
<td>Nitric acid oxidation</td>
</tr>
<tr>
<td>Golden Spec</td>
<td>Pressure cyanidation</td>
</tr>
</tbody>
</table>

This diversity of process alternatives demonstrates the importance of considering each orebody on a project specific basis.

Foo and Bath have published options diagrams (Figures 2a and 2b) for the metallurgical testing of gold ores, which provide useful aids to the design of testwork programmes. However, it is important to marry the metallurgical testing with continued economic analyses of each process. Simply achieving high levels of gold recovery at an acceptable cost does not necessarily mean that the optimum process route has been selected.

It is stressed that the selection of the final process route should not be made too early in the assessment process and, especially, without an appropriate level of detail in the metallurgical testwork. The Kanowna Belle case study demonstrates how the ranking of roasting and biological oxidation was reversed between the prefeasibility and final feasibility study stages, due largely to an improved level of recovery from roasting and lower recovery from biological oxidation which were both determined in pilot plant testwork. Furthermore, the level of detail in the final study highlighted a greater difference in costs than had previously been determined. In view of the decision of the project owners to take both processes to pilot plant testing, this reversal in ranking did not adversely affect the timetable for project development and allowed the optimum process selection to be made.
Figure 2(a)
Metallurgical Testing
of Refractory Gold Ores
Phase I

A

Yes

IS ORE AMENABLE TO PRECONCN?

No

OPTIMISE PRE-CONCN. CONDITIONs

ESTABLISH BASELINE CYANIDE EXTRACTION FOR WHOLE ORE

ESTABLISH BASELINE EXTRN. FROM CONC.

IS CARBON PRESENT?

No

Yes

COMPARE DIRECT CYANIDATION WITH CIL

IS CARBON PREG-ROBBING?

No

Yes

ESTABLISH NEW BASELINE EXTRACTION FOR CIL

IS EXTRACTION ACCEPTABLE?

No

Yes

PRE-AERATION TESTING

IS CYANIDE CONSUMPTION ACCEPTABLE?

No

Yes

CYANIDE CONSUMPTION REDUCED?

Yes

OPTIMISE CIL CONDITIONS

DEVELOP FLOWSHEET

START PRE-OXIDATION TESTING

B
Figure 2(b) Metallurgical testing of Refractory Gold Ores Phase II

Decision Tree:

1. Is ore amenable to preconcn?
   - Yes: Prepare concentrate
   - No: Continue testing of alternative processes

2. Is sulphur content high?
   - Yes: Bacterial oxidation
   - No:
     - Dry grind: Nitric low temp.
     - Wet grind: Nitric high temp.
     - Roasting
     - Bacterial oxidation
     - Pressure oxidation
     - Chlorination
     - Sirosmelt
     - Chlorination

3. Is extraction acceptable?
   - Yes: Reagent consumptions reasonable?
     - Yes: Develop flowsheet
     - No: Preliminary economic valuation
   - No: Continue testing of alternative processes

4. Preliminary economic valuation:
   - Favourable?
     - Yes: Pilot testing
     - No: Continue testing of alternative processes
FACTORS FOR CONSIDERATION IN REFRACTORY PROCESS SELECTION

Based on Minproc’s experience on numerous projects, the following factors are all considered to be of importance in selecting a process for treatment of refractory gold ores. All factors should be taken into account at an early stage and that process options should be kept open for as long as possible due to the potential for unforeseen issues having a deleterious impact on the economics of a particular process.

Gold Mineralogy

It is particularly important that the occurrence of gold in the ore is understood at an early stage in the project evaluation. An example in point is the Kanowna Belle project, where identification of the importance of arsenic volatilisation allowed roasting conditions to be optimised for gold recovery. Similarly, at the Youanmi mine, identification by various biological oxidation researchers of the occurrence of gold with arsenopyrite, and not with the other, less reactive sulphide minerals such as pyrite, has allowed the design of a process in which only a relatively low degree of sulphide oxidation is required to achieve maximum gold recovery. Association of gold with graphitic carbon can indicate the need for a process which eliminates the carbon prior to cyanidation. This can be integral with oxidation in roasting, but may require an additional process step if hydrometallurgical processes are used.

A variety of techniques, including conventional mineralogy (Henley 1991), microbeam techniques (Chryssoulis et al 1993) and diagnostic leaching, are available and should be used in an integrated approach, both before and during the testwork programme. Such techniques are particularly useful for assessing variations in gold mineralogy throughout an orebody.

Diagnostic leaching should be used with care and caution, ensuring that the various leach stages are carried out correctly and the results analysed properly. By their nature, refractory ores are difficult to characterise by a limited number of diagnostic leach tests.

Arsenic Content

The arsenic content of an ore is important for a variety of reasons. A high arsenic content generally means that a careful assessment of disposal methods is required. Its presence, in significant quantities, virtually eliminates concentrate roasting as a viable alternative because of the high costs in fixing arsenic for safe disposal and the shrinking size of the arsenic market. It should, however, be noted that alternative methods (Lunt et al 1991, Khoe et al 1994) are in fairly advanced stages of development and offer the potential for relatively low cost disposal. This would reduce one of the major advantages for hydrometallurgical oxidation routes. Conversely, a low arsenic content can indicate the potential for high gold recovery from roasting.

A high arsenic content and a low iron content in an ore will indicate the potential for arsenic stability problems following neutralisation of oxidised slurries. For BIOX®, it has been indicated (Broadhurst 1994) that an Fe/As ratio of greater than three is required to achieve acceptable results. Testwork on the Redox® process has indicated that similar results can be achieved at significantly lower ratios, perhaps due to the greater oxidation potential. This was a major factor in the initial process selection at Bakyrchik.

The results of the Sansu project evaluations suggest that, whilst oxygen-assisted whole ore roasting is suitable for ores with a low arsenic content, there may be an upper limit beyond which the arsenic is not rendered stable within the bed.

Sulphide Content

The sulphide content of an ore can be important for a number of reasons.

Having a high sulphide content proportionately increases the cost of neutralisation. A high sulphur content can render discharge to the atmosphere from roasting unacceptable and also adversely impact the economics of an acid plant for capture due to a small local market. Conversely, a high sulphide content can render whole ore roasting more attractive due to a lower fuel requirement. Use of oxygen significantly reduces the
sulphide content required for autothermal roasting. The ratio of sulphide sulphur to the carbonate content of an ore will dictate the need or otherwise for downstream capture of sulphur dioxide from whole ore roasting.

The power costs for oxidation processes, in particular biological and pressure oxidation, are proportional to the amount of sulphur that needs to be oxidised. This will tend to improve the relative economics of processes that are power efficient, such as Redox® pressure oxidation and, especially, roasting. It can easily be forgotten by the geologists in charge of exploration that the oxidation process will need to be sized not only on the ore throughput, but also on the tonnage of sulphide sulphur to be oxidised. Inadequate information on the variation in sulphur assays throughout an orebody can cause the mine to bottleneck on the oxidation circuit or for capital to be wasted on surplus oxidation capacity.

**Gangue Mineralogy**

The acid-consuming carbonate content of an ore is of particular significance in process selection. It can impact in a number of ways, including:

- adsorption of sulphur dioxide from roaster operations;
- requirement for acidulation prior to pressure oxidation or during biological oxidation;
- requirement for additional carbonate additions for carbon dioxide levels in biological oxidation if too low;
- reduction of downstream neutralisation costs for hydrometallurgical routes.

The presence of graphitic carbon can be deleterious to a gold recovery operation, due to its preg-robbing potential and its common association with, and occlusion of, gold. Unfortunately, it tends to be preferentially recovered to a flotation concentrate and, hence, concentrate treatment routes are more sensitive to its presence. Roasting processes have the advantage that conditions can be tailored to burn off the carbon prior to cyanidation, as well as using carbon as a part of the calorific balance. However, the higher temperatures required can adversely affect gold recovery due to encapsulation and, if the burning is not successful, the high temperatures can increase the potential for preg-robbing. Other process routes can require its separation by physical techniques prior to oxidation, as is practised at Bakyrchik, or the use of an additional carbon passivation technique, such as the use of CIL to treat carbonaceous BIOX® product, at Sansu.

**Ore Variability**

Ore variability can impact on process selection in a number of ways. Of particular note is the presence or otherwise of a significant transition or partially oxidised zone. From a metallurgical perspective, this ore type can be the worst material encountered in an orebody, being refractory in nature and also too highly oxidised to allow good concentration ratios in flotation. Open pit developments are particularly sensitive to these zones, as they are the first refractory ore to be treated, thus necessitating commissioning to be carried out on potentially the worst material. If autothermal roasting is required, the presence of such a zone can be of critical importance to commissioning, as an inadequate sulphur content in the concentrate can prevent roasting operations from proceeding in a satisfactory or economic fashion. Similarly, poor concentration ratios can potentially cause washouts in biological oxidation plants. Treatment of such ore types in Ghana have also encountered high clay contents which have been deleterious to flotation, thickening and filtration.

Flotation of transitional ore types can be improved by such techniques as controlled potential sulphidisation, controlled pH flotation, desliming of flotation feed and by increasing the flotation residence time.

As the design of an oxidation circuit is based on the quantity of sulphur to be oxidised, it follows that variations in the sulphide mineralogy will impact directly on plant capacity and operation. Variations in the relative proportions of the various sulphide minerals will need to be taken into account, in particular the presence of the reactive but acid-consuming mineral pyrrhotite.
Planning for the presence of pockets of minerals deleterious to a process is also important. These could include minerals toxic to bacteria (e.g., mercury, lead, etc.) or glass-forming minerals in a roasting process.

Another variation could relate to the degree of oxidation required for maximum gold recovery. Some samples can exhibit high gold recoveries at low oxidation levels, whilst others indicate that maximum oxidation is required.

**Project Scale**

For most of the oxidation processes, there are limitations on the capacity of particular unit operations. In roasting, the diameter of a roaster is constrained by structural design, whilst, for biological oxidation, the reactor capacity is currently limited by a maximum agitator size of around 500 kW. Conversely, the relative economics of pressure oxidation appear to increase with throughput, primarily because of fixed costs associated with the ancillary oxygen plant, despite the need for multiple autoclaves. Certainly, the capital costs of processes such as biological oxidation will increase at a higher rate once the maximum reactor size has been reached. The original Sansu BIOX® plant required 18 reactors arranged in three trains and it is likely that, at its maximum capacity, a total of 36 reactors will be in operation. Therefore, not only are there fewer economies of scale as the throughput increases, but, in practice, the unit costs increase due to the need for a more complex distribution system of services such as air and cooling water.

High treatment throughputs can also impact in the following ways:

- High consumption of reagents or utilities that can exceed the capacity of the associated infrastructure to support the project. For example, the need to significantly increase the Goldfields Water Supply Scheme to Kalgoorlie to provide high quality water to a pressure or biological oxidation plant, or the requirement at AGC for large quantities of lime to be imported from Europe due to the limited resources in Ghana.

- Environmental constraints are frequently determined by the quantities of a particular species to be emitted. For example, the licence for the roasters at Gidji treating concentrates from Kalgoorlie stipulate the maximum quantity of sulphur dioxide that can be emitted. Similarly, it is probable that if the sulphur output of Kanowna Belle had been significantly larger, then the permitting of a roaster operation would have been a more significant issue.

**Incremental Gold Recovery**

Several gold projects with which Minproc has been associated display relatively high gold recoveries, say 70-80%, using conventional cyanidation, perhaps with a fine regrind of flotation concentrates. One example is the Macraes Flat mine in New Zealand. In this situation, the incremental process economics are particularly sensitive, especially if the ore grade is low. This tends to favour processes with lower operating costs, such as fine grinding, unless a more expensive oxidation process can provide recovery advantages. The Macraes Flat operation has been a highly successful operation using conventional fine grinding, despite achieving only 70-75% recovery. Ongoing testwork into a variety of processes has shown that higher recovery can be achieved, but until the recent investigation of Newmont’s pressure oxidation process, these did not prove to be economic.

It is Minproc’s opinion that advances in fine grinding developed in the base metals industry have the potential to significantly improve the economics of this process through a significant reduction in power consumption.

**Flotation Performance**

Flotation performance is of great significant in evaluating overall process economics. Indeed, this should be considered as an integral component of the refractory process evaluation. A particular example is the AGC Sansu project, where whole ore roasting appeared to be relatively attractive until reagent optimisation testwork confirmed that higher levels of flotation recovery could be achieved. Other operations have been unable to achieve acceptable recoveries and concentration ratios, and have selected whole ore treatment
routes such as roasting or pressure oxidation, Minahasa being one such example where whole ore roasting is employed.

The achievement of a satisfactory concentrate grade is of particular importance to concentrate roasting economics. Each ore type needs to be assessed according to its mineralogy to determine which concentration ratios of sulphide and carbon (if present) permit autothermal roasting, i.e., the grade at which no fuel needs to be added for combustion.

The variability in ore types discussed above is particularly pertinent to flotation performance. Indeed, the presence of a significant transition zone can dictate the design of a flotation circuit and the concentration ratio that is achievable, which, in turn, controls the design of the refractory process stage. Achieving autothermal concentrate grades can be particularly difficult in this event.

**Site Specific Environmental Considerations**

The situation in Western Australia, where the discharge of sulphur dioxide is permitted, is unusual and, obviously, favours roasting. However, another environmental situation that favoured roasting over biological oxidation at Kanowna Belle was the difficulty in discharging hypersaline water back into the environment, even after cyanide destruction. Due to the extreme sensitivity of the oxidising bacteria to thiocyanate, it was highly likely that a significant amount of tailings dam decant water would have needed to be discharged, although this would have been difficult due to its high saline content.

With high arsenic ores, the need for decant water to be discharged rather than recycled is of particular environmental sensitivity. Processes such as BIOX®, which require large amounts of wash water, are particularly affected by this potential issue. In this situation, it is important to test the long term stability of oxidised products for all base metals and other toxic components. Whilst many can comply with the USEPA TCLP test, this is not necessarily an indication of long term stability in tailings dams and other tests should be included in the evaluation procedure.

**Project Location and Infrastructure**

Kanowna Belle and Sansu are important examples of how the project location can have a significant bearing on the selection of a refractory process. At Kanowna Belle, the location resulted in high costs for quality water, power and lime, all of which adversely affected the relative economics of biological oxidation. At Sansu, the choice of biological oxidation over pressure oxidation was highly affected by the remote location and the perceived difficulties in operability and maintainability of the latter process. This compares with Nevada, for example, where the infrastructure has a greater capability of supporting sophisticated processes such as pressure oxidation.

Biological oxidation is relatively disadvantaged when building a plant at altitude, as the inefficiencies of using air to provide the oxidant in a stirred reactor are exacerbated at lower pressures and in the more rarefied atmosphere.

**Water Quality and Availability**

The problems of water quality on the biological oxidation process have been described above in relation to Kanowna Belle. It is important to note that, while the improvements in the process reduced direct water consumption to 8.4 m³/h, the water consumption in the cooling system was still 18.1 m³/h. A hypersaline water cooling system was developed and pilot tested, but was still considered to be a major risk, as current industrial cooling processes are only operating at chloride levels 10 times lower.

However, the problems of saline water in biological oxidation processes were relatively minor compared with those for pressure oxidation, which required a chloride level of less than 150 ppm, lower than that present in the Goldfields Scheme water.

The potential ability to operate in poor quality water are perceived advantages of processes such as Activox® and Redox®.
Power Costs

In the evaluations described above, the high cost of power in Kalgoorlie can disadvantage biological oxidation, which has a relatively high power consumption when applied to concentrates. However, at Sansu, the availability of cheap hydro-electrical power meant that this cost differential is significantly reduced and favours large scale biological oxidation. As determined by Foo et al (1989), the ranking of processes according to power consumption changes quite significantly between whole ore and concentrate cases and for different mineralogical compositions.

Availability of Neutralisation Reagents

The biological oxidation studies for Kanowna Belle were undertaken after the implementation of Gencor’s BIOX® process at Wiluna. Both projects are located in Western Australia. However, a significant difference between the two projects is the availability of good quality carbonates close to the Wiluna mine for use in the neutralisation step. The nearest occurrence of similar material to Kalgoorlie is over 500 km away, necessitating the use of limestone from Loongana in the Nullarbor region, increasing the operating costs by $18.77/t.

The high cost of neutralisation reagents can significantly improve the economics of processes, such as whole ore roasting, which can utilise any carbonate component of the ore for neutralisation of the sulphur released during oxidation, or which do not oxidise the ore, such as fine grinding.

Cyanide Consumption and Costs

Several process comparisons have focussed on the relative economics of the pretreatment steps and have assumed that the cyanide consumption in CIL is the same for each process. However, examination of laboratory data in a number of applications has indicated a significant differential in the cyanide consumption, particularly between pressure oxidation and biological oxidation. In some instances, this differential can be as high as 15 kg/t NaCN, which can significantly impact on the process economics due to the increased cost of cyanide destruction in water discharged to the environment.

Project Life

Many of the gold projects in Australia have been initiated on the basis of a relatively short project life, although some of these have outlasted initial predictions. Whilst this situation is less likely to repeat itself as the deposits are extended into the sulphide zones, some of the sulphide deposits are relatively small. An example of this is the Harbour Lights BIOX® project which had a life of only three years.

The pressure oxidation process is most sensitive to project life due to the costs of installing the associated oxygen plant. However, the potential incremental recovery and lower operating costs that may be achieved using this technology can counteract the higher capital costs over an extended project life.

Ability to Pilot

It is generally acknowledged that pilot plant testwork is required prior to installation of a refractory process. This certainly applies to greenfield projects and those where the incremental recovery is high.

Most processes require 200-300 kg of concentrate sample from each major ore type and the testwork programmes can be completed within one to two months. Whole ore processes typically require 500-1 000 kgs of sample. In contrast, the biological oxidation pilot programmes can take four to six months per ore type and require over 600 kgs of concentrate. The reasons for the extended period are the long retention time within the process, which extends the time to examine a particular parameter, and the period required to raise the bacterial activity to an appropriate level.

For some projects, the sample requirements can present problems, especially in situations where the concentration ratio in flotation is high, where there are a variety of ore types to be evaluated or where the
sulphide zone is not easily accessed by adits or drilling. As an example, the Kanowna Belle pilot plant programmes required over 40 tonnes of ore to be obtained from a depth of over 120 metres using drilling techniques. A mitigating factor was the relative consistency of the orebody, which permitted the acquisition of a single bulk composite.

In this context, it is also important to ensure that the concentrate sample has a representative grade. Whilst lower grade samples allow some of the sample size requirements to be circumvented, they can produce misleading results. Reagent consumption can be significantly changed, especially if the additional bulk is made up of reactive carbonates. Also, the critical threshold for effects such as bacterial toxicity or vitrinisation and encapsulation in roasting may not be achieved in a lower grade sample.

**DISCUSSION**

Evaluation of a number of refractory gold projects has highlighted the need to examine each orebody individually, in terms of both mineralogy and external factors, such as location, size, etc. There is not yet any process which has been developed which is as widely applicable to refractory ore treatment as CIP or CIL techniques are to oxide orebodies.

It is extremely difficult to propose a generic programme for the evaluation and selection of a refractory process. These can vary from situations such as Ashanti’s on the Sansu project, where both whole ore and concentrate processes were highly applicable, necessitating a long and exhaustive evaluation of the alternatives, to one such as Minahasa, where the preliminary testwork programmes and mineralogy demonstrated that whole ore roasting was a more obvious selection without the need for more extensive studies and testwork.

Perhaps the most important step in selecting a refractory process for a particular orebody is to ensure that the mineralogy and metallurgy are well understood prior to making any decisions. These then need to be considered in the context of the constraints of the process location. It should then be practicable to select a shortlist of suitable technologies for more detailed evaluation.
REFERENCES


