# MAKING THE RIGHT SELECTION: A COMPARATIVE ANALYSIS FOR THE TREATMENT OF REFRACTORY GOLD CONCENTRATES


## ABSTRACT

Building on work completed in earlier papers, the current paper presents a techno-economic evaluation of two recently demonstrated technologies for treatment of arsenic containing refractory gold concentrates. Using defined project parameters and inputs, the authors compare capital and operating cost estimates for pressure oxidation (POx), and the Albion Process™. The paper incorporates data now publicly available from the Albion Process™ plant, which has operated at the GeoProMining Gold (GPM Gold) project in Armenia since 2014, as well as recent POx circuits.



Key Words: Albion Process, Autoclave, Pressure Oxidation


## INTRODUCTION

The genesis for this paper began in 2005 when a similar refractory gold extraction comparative study was undertaken by authors mainly from Jacobs' predecessor Aker Solutions [3]. The previous study compared existing established refractory gold extraction processes with the newly emerging Albion Process™. With a continued strong demand for options to treat refractory gold deposits, the Albion Process™ plant which has been in operation for more than three years at GPM Gold in Armenia now provides operational and capital cost information.

We have chosen to constrain this paper to only comparing pressure oxidation (POx) with Albion Process™, with both processes fed by sulphide flotation concentrates. To make the comparison more direct we have also assumed that the upstream materials handling, crushing, grinding and flotation plant sections are identical for both options, as are the downstream gold extraction (Carbon in Leach [CIL] circuit and gold room) and tailings handling systems.

We acknowledge there will be some inherent differences due to the extraction processes used and their management needs in regards to chemistry and plant water balances.

It is acknowledged that there are other relevant processes which can be used for treating refractory gold in both whole of ore and concentrates feed applications; these include roasting (using suppliers such as Outotec [Lurgi] and Technip [Dorr Oliver] and biological oxidation such as Outotec BIOX). These require close liaison with specialty vendors and extensive test work with those particular vendors. There is also the option of producing a concentrate for sale to a larger smelter complex.

Including all these options in this review would require a high degree of open exchange with a number of competing parties and therefore this review has been constrained to comparing the POx process with the Albion Process™. It is considered that the Albion technology is sufficiently proven and mature to be viable for practical consideration for refractory gold applications. The GPM plant has now been in operation for more than three years and there are six Albion plants in operation globally in a variety of locations and treating a variety of commodities.

For the ease and accuracy of comparison we have based comparative costs on a project in North America with a similar gold output to the GPM Gold project.

A conservative design availability of 85% is used in this paper for the POx circuit. In comparison the Albion Process™ availability is considerably higher at 90%. Recognising the difference in plant availability for the purposes of this comparison is fundamental for the sizing of major equipment in each circuit.

It is strongly acknowledged that, for any refractory gold project, there is a need to have sufficient and early high quality testing and studies completed in areas such as mineralogy, geometallurgy, floatability, gravity recovery, grindability, rheology and cyanide extraction. These are typical requirements before the critical work of developing engineering options for the process route commences. A formal and staged engineering study approach using experienced teams and established study benchmarking is vital to working towards selection of a preferred process option(s) for the specific project.

## ASSUMPTIONS

This is a comparative study between two refractory gold oxidation methods. As such the philosophy adopted has been to limit the comparison to the specific plant areas that are significantly different. Therefore, this gives an input stream of flotation concentrate and an output stream of oxidised slurry being fed to the CIL and subsequent downstream recovery and tailings.

The concentrate tonnage and composition used in this paper is the same as the actual GPM Gold material and POx performance has been implied for that feed material. The actual GPM Gold plant also directs the flotation plant scavenger tailings to the CIL plant and this approach has been adopted for both the POx and Albion Process™ circuits studied in this comparison. Based on the actual GPM Gold plant operating experience and current practice, any future plant similar to the GPM Gold plant would be modified to eliminate the discharge thickener and change the Albion Process™ leach reactors from nine 240 $m^3$ tanks to six 340 $m^3$ tanks. These flowsheet changes have been incorporated into this comparison.

Other assumptions that have been made include the following:

- A North American generic site with a 2018 cost structure is the comparison. The specific site is flat with stable foundations and good ground conditions at an elevation of 1200 metres above sea level.
- Any reagents required for the oxidation process are included in the costings developed for this paper. This includes sourcing, mixing, storage and distribution as needed for lime, limestone, oxygen etc.

## MINERALOGY

For the ore body studied in this comparison, pyrite, arsenopyrite and pyrrhotite are the major sulphide minerals present which report to the sulphide concentrate. Gold occurs as native free gold, finely dispersed gold in arsenical sulphide, gold tellurides and secondary native gold remaining after oxidation of sulphides and tellurides. Silver is present in its native form in quartz, chalcopyrite and pyrite as well as silver tellurides. The main gangue minerals are quartz, talc and chlorite, with minor magnesite, dolomite and calcite.

The sulphide concentrate is produced from a typical milling and bulk flotation circuit. The elemental and mineralogical composition of the sulphide flotation concentrate used to develop the comparison between the POx circuit and the Albion Process™ circuit is summarised below:

*Table 1 - Flotation Concentrate Elemental Assay*

| Chemical Element | | Units | Value |
|---|---|---|---|
| Arsenic | As | % w/w | 2.66 |
| Iron | Fe | % w/w | 18.71 |
| Sulphur | S | % w/w | 17.26 |
| Silicon | Si | % w/w | 17.89 |
| Oxygen | O | % w/w | 30.76 |
| Magnesium | Mg | % w/w | 4.80 |
| Calcium | Ca | % w/w | 1.79 |
| Other | - | % w/w | 6.13 |
| Gold | Au | g/t | 47.28 |
| Silver | Ag | g/t | 48.43 |

*Table 2 - Flotation Concentrate Predominant Minerals*

| Mineral | Chemical Formula | Units | Value |
|---|---|---|---|
| Pyrite | $FeS_2$ | % w/w | 23.9 |
| Aresnopyrite | FeAsS | % w/w | 5.8 |
| Pyrrhotite | $Fe_{0.877}S$ | % w/w | 5.18 |
| Chalcopyrite | $CuFeS_2$ | % w/w | 1.0 |
| Quartz | $SiO_2$ | % w/w | 33.9 |
| Calcite | $CaCO_3$ | % w/w | 2.23 |
| Dolomite | $CaMg(CO_3)$ | % w/w | 2.18 |

| | | | |
|---|---|---|---|
| Magnesium Oxide | $MgO$ | % w/w | 2.15 |
| Magnesite | $MgCO_3$ | % w/w | 5.82 |
| Talc | $3MgO*4SiO_2*H_2O$ | % w/w | 5.92 |
| Other | | % w/w | 11.92 |

## BASIS AND METHODOLOGY OF ESTIMATE

The cost estimates for this comparison are based on the following documents: process design criteria, mechanical equipment list (process and utilities equipment), material take offs (MTOs) (includes ducting, bins, etc.), block flow diagram, site plot plans and general arrangement drawings, project design basis (Aspen Capital Cost Estimator [ACCE] specifications only) and escalated prior quotations. The ACCE package generated pricing on a majority of the process and utilities equipment as well as most bulk materials with remaining equipment and bulk material pricing based on Jacobs in-house pricing (consistent with pricing on recent projects) and cost data from published estimating sources and other supporting engineering documents

The estimates were prepared per Jacobs' guidelines and standards for a Class 5 Capital Cost Estimate, accuracy range +50% / -50%. The estimates identify the capital costs associated with the flowsheets described below.

The estimates represent modelled quantities developed from the Jacobs-customised software program Aspen Capital Cost Estimator (ACCE) for all major direct cost accounts. Where specific data was not available, data was factored based on Jacobs historical data. Such quantification methods are suitable to support a Class 5 estimate.

A major mechanical equipment list was generated with conditions of service sufficient to support equipment pricing. Major equipment pricing was based predominantly on escalated previous quotes from similar projects and from ACCE system pricing. Engineering design data for the equipment specified was used to generate ACCE pricing for the quoted packages.

Approximately 73 - 78% of the purchased equipment costs (PEC) in the estimate represent escalated prior quotes and 22 - 36% represent ACCE pricing based on preliminary design data sheets, preliminary conditions of service, capacities and specifications. Approximately 1% of the PEC in the estimate represents in-house or historical pricing data.

Bulk MTOs were generated by ACCE for each of the relevant accounts based on the equipment sizing, capacities, specifications and conditions of service. Building costs are based on cost per square metre rates from recent purchases and in-house estimates. Design development allowances (DDAs) and MTO allowances for each relevant account were established by estimating and discipline engineering personnel, based on Jacobs' experience.

Jacobs prepared field construction installation hour estimates via ACCE based on Jacobs' standard estimating labour units, which represent U.S. Gulf Coast rates at ideal conditions for a mid-size project at a greenfield site. Productivity adjustments were then developed for the North American generic site and applied to those installation hours.

The remainder of the direct costs were developed using customised ACCE equipment cost modelling software. Construction indirect costs, engineering and other costs, as well as the overall area and total cost summaries were developed based on percentages and factors from historical project data based on the defined scope. Metrics and benchmarking analyses were then completed, along with the overall assembly and finalisation of the basis of estimate and review packages.

The operating costs development comprises: power consumption; reagents consumptions; operating and maintenance labour and materials. Power consumption estimates were factored from the equipment list. Reagent consumption rates have been developed based on the process design criteria. The costs of maintenance were based on data typical of the project location, factored from the installed capital and taking into account the service and operating conditions of the equipment. For the purposes of this comparison it has been assumed that the labour requirements for both circuits would be equivalent. This assumption is based on the availability of an experienced workforce in North America and may not hold for all geographies.

Prices for reagents, utilities and consumables have been sourced from Jacobs' North American database of recent pricing.

## PROCESS FLOWSHEETS

Both processing routes treat a flotation concentrate containing predominantly pyrite, with minor arsenopyrite. The GPM Gold concentrate is relatively clean with no appreciable amounts of mercury, caesium, selenium or vanadium. The sulphur oxidation and gold liberation are completed using either the Albion Process™ or POx.

### Albion Process™ Flowsheet

The flowsheet for the Albion Process™ circuit is based on the circuit installed at GPM Gold and incorporates learning based on the performance of this circuit.

In the Albion Process™ flowsheet, the flotation concentrate Thickener underflow concentrate is pumped to the IsaMill™ feed pumpbox where it is combined with media before being pumped to the M3000 IsaMill™. The IsaMill™ is specified to achieve a grind size of 80% mass passing 12 to 14 µm. The discharge slurry is then pumped to an agitated concentrate storage tank with over eight hours surge capacity to allow the leach to continue to operate when IsaMill™ maintenance activities are performed. The concentrate slurry is then transferred to one of the first three Albion Process™ leach reactors. The oxidative leach circuit flowsheet consists of six, 340 $m^3$ Albion Process™ leach reactors fabricated from lean duplex alloy steel (LDX2101) connected with launders allowing tank by-passing during maintenance events. Each reactor is fitted with a 160 kW dual impeller agitator, with oxygen delivered by a bank of six supersonic HyperSparge™ oxygen gas injection lances. The process is designed to run autothermally at or around 93°C.

The pH in each reactor is maintained between 5.0 to 5.5 through dosing of limestone slurry. The limestone slurry is produced in an on-site limestone milling plant, with a capacity of 6 t/h. The limestone is milled to an 80 % mass passing size of 75 µm in a ball mill operated in closed circuit with cyclones. The cyclone overflow reports to a 150 $m^3$ agitated distribution tank and circulates through the oxidative leach circuit by ring main.

Oxygen for the Albion Process™ and CIL is provided by two 60 t/d Vacuum Pressure Swing Adsorption (VPSA) plants with up to 98 t/d going to the Albion Process™ and the balance to the CIL plant. The turndown capability in the VPSA means the oxygen generating capacity can be reduced when less oxidation is required.

The leach discharge is around 30% solids and is mixed with flotation tailings before feeding the CIL circuit.

The Albion Process™ residue treated in the CIL circuit is characterised by low lime and cyanide consumption as a result of the continual neutralisation of iron and acid through the addition of the alkali limestone during oxidation. This process also prevents the formation of element sulphur. The cyanide consumption for the Albion Process™ residue is around 4kg cyanide per tonne of residue.

### Pressure Oxidation (POx) Flowsheet

In the POx flowsheet, the Flotation Concentrate Thickener underflow concentrate is fed via a piston diaphragm feed pump in a duty standby arrangement into a single 5 compartment autoclave vessel. The autoclave vessel is equipped with a bottom-inlet sparge system to introduce gaseous oxygen, coolant water, and steam (for initial heat-up).

The oxidised slurry is then discharged from the last autoclave compartment to a flash tank where pressure reduction is accomplished by a ceramic lined control valve followed by a choke tube and fixed choke. The flash tank overheads are ducted to a venturi scrubber. The vent from the autoclave is reduced in pressure through a ceramic lined control valve to the POx vent spool before going to a dedicated venturi scrubber. The pressure safety salves (PSV's) included in the system discharge to a different vent spool and cyclonic separator, equipped with water addition points to clean the system when a PSV lifts. Gas and non-condensables discharge from the top of the cyclonic separators, with water and condensables flowing to the scrubber pump box, to be pumped to the decant thickener.

The autoclave support systems include a high pressure seal water system, demineralisation water package, stand-by / start up boiler unit, glycol handling system, coolant injection system and seal flushing system as well as process cooling. Oxygen for the autoclaves is provided by a VPSA plant.

From the autoclave circuit the hot flashed slurry enters the hot cure circuit. The hot cure circuit not only allows cooling of the slurry for the downstream CIL cyanidation circuit but it also aids in the conversion of basic iron sulphate to ferric sulphate by lowering the temperature and providing retention time for iron and arsenic precipitation.

After slurry cooling, the cooled slurry is pumped to the Counter-Current Decantation (CCD) circuit which consists of a decant thickener and two CCD's.

The purpose of the CCD circuit is to wash the POx slurry by adding wash water counter current to the slurry flow to remove acid and if applicable, the soluble copper from the gold bearing solids. The concentrated copper solution can report to a copper precipitation circuit for recovery (if economic) while the washed gold bearing solids are pumped to the neutralisation circuit prior to being combined with the flotation tail in the CIL circuit to recover the gold.

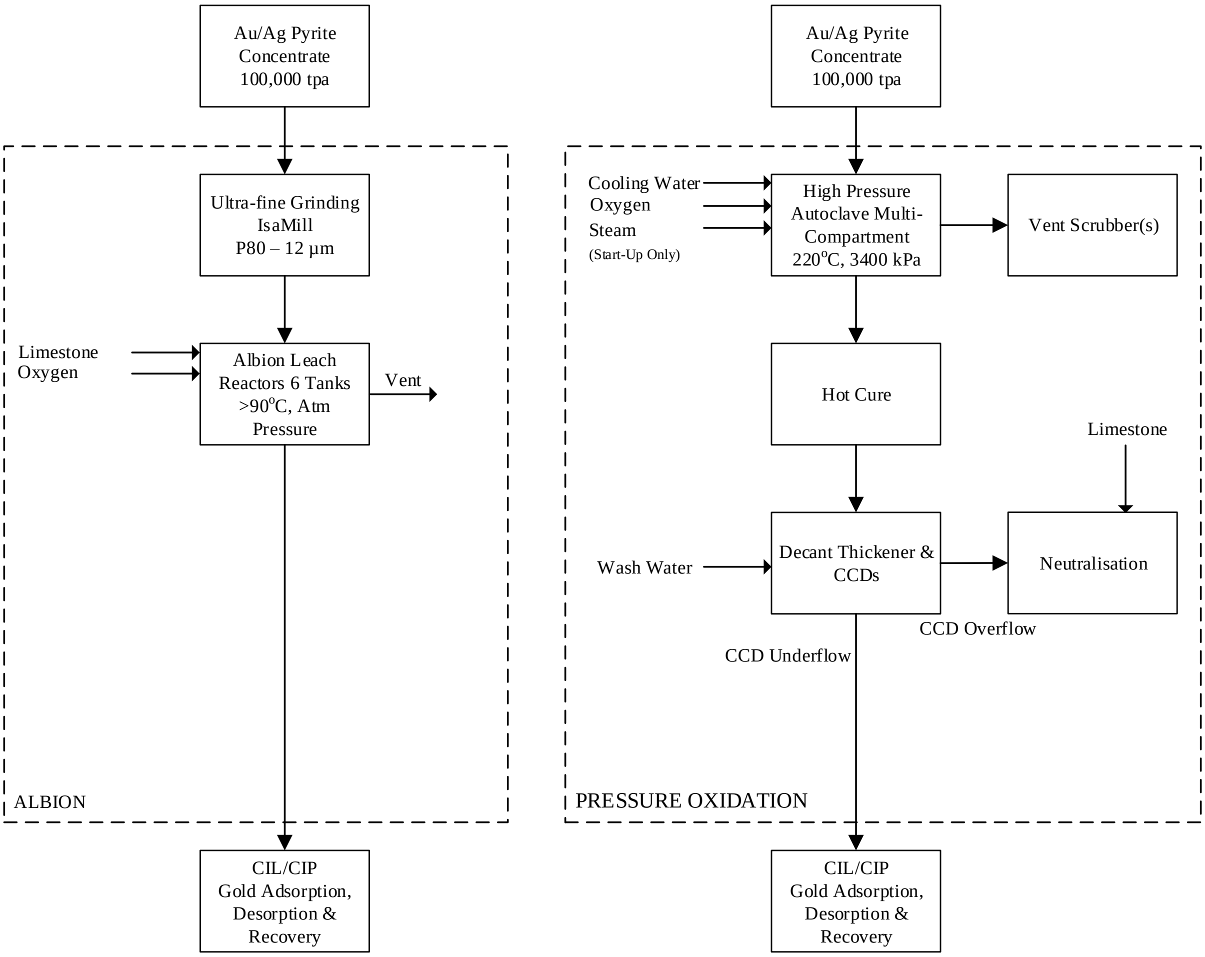


*Figure 1 – Albion Process$^{TM}$ and POx Flowsheet Comparison*

## POX CHEMISTRY

The POx process was originally developed for the treatment of base metal concentrates before being adapted to treat gold containing pyrite and arsenopyrite ores and concentrates. The process uses an autoclave operating typically in a temperature range of 190 to 230°C with an oxygen over pressure of 350 to 700 kPa(g) and retention times that vary from 60 to 90 minutes. Sulphide oxidation in the POx autoclave is typically greater than >98% for most ores and concentrates. The feed density of the sulphide concentrate to the autoclave is regulated to provide sufficient heat, generated by the exothermic oxidation reactions, to maintain the desired operating temperature of the autoclave. The following oxidation and hydrolysis reactions occur in the autoclave when pyrite and arsenopyrite react with oxygen:

Pyrite: $2\ FeS_2 + 7\ O_2 + 2\ H_2O \leftrightarrow 2\ FeSO_4 + 2\ H_2SO_4$

$$2\ FeSO_4 + H_2SO_4 + \frac{1}{2}\ O_2 \leftrightarrow Fe_2(SO_4)_3 + H_2O$$

$$Fe_2(SO_4)_3 + 3\ H_2O \leftrightarrow Fe_2O_3 + 3\ H_2SO_4$$

Arsenopyrite: $2\ FeAsS + H_2SO_4 + 7\ O_2 + 2\ H_2O \leftrightarrow 2\ H_3AsO_4 + Fe_2(SO_4)_3$

$$2\ H_3AsO_4 + Fe_2(SO_4)_3 \leftrightarrow 2\ FeAsO_4 + 3\ H_2SO_4$$

**ALBION CHEMISTRY**

The Albion Process™ comprises a patented combination of fine grinding and atmospheric leaching. The first step uses ultra-fine grinding IsaMill™ technology to produce a sufficiently fine and narrow particle size distribution. The second step is sulphide oxidation achieved through supersonic oxygen injection into leach reactors operating at near neutral conditions (pH 5.5). The chemical reactions which form the basis of the Albion Process™ require the addition of oxygen to oxidise the pyrite and arsenopyrite while limestone is added to continually neutralise acid generated by the oxidation reactions.

Pyrite: $4\ FeS_2 + 11\ O_2 + 18\ H_2O + 8\ CaCO_3 \leftrightarrow 4\ FeO.OH + 8\ CaSO_4.2H_2O + 8\ CO_2$

Arsenopyrite: $2\ FeAsS + 7\ O_2 + 4\ H_2O + 2\ CaCO_3 \leftrightarrow 2\ FeAsO_4 + 2\ CaSO_4.2H_2O + 2\ CO_2$

The exothermic chemistry results in autogenous reactions, operating at 93ºC with no requirement for additional heating or cooling. For pyrite, the concentrate is ground to 80 % passing 10 to 12 µm (in the case of the GPM Gold plant, 12 to 14 µm) and the extent of oxidation can be varied depending on the level of oxidation required for certain feed types. In the case of GPM Gold, the design sulphide sulphur oxidation extent is 76 % to achieve over 93 % gold recovery, although the plant has been reported to operate at 60 % sulphide sulphur oxidation and achieved greater than 95% gold recovery [7]. To achieve the sulphide sulphur oxidation extents achieved in the GPM Gold plant requires a typical residence time of 30 hours.

**CAPITAL AND OPERATING COST ESTIMATE COMPARISON**

The capital and operating cost estimates prepared for the Albion Process™ and POx flowsheets are based on the process design criteria, equipment list and other supporting documentation.

*Table 3 - Capital and Operating Cost Estimate Comparison*

| | Albion Flowsheet | POx Flow sheet |
|---|---|---|
| Throughput | 100,000 tpa | 100,000 tpa |
| Gold Leach Extraction | >93% | >94% |
| **Capital Cost USD** | **66,200,000** | **95,900,000** |
| Direct Costs | 30,200,000 | 44,500,000 |
| Indirect Costs | 9,700,000 | 13,500,000 |
| EPCM | 8,700,000 | 12,700,000 |
| Contingency | 15,300,000 | 22,100,000 |
| Capital Spares & First Fills | 2,300,000 | 3,100,000 |
| **Annual Operating Cost USD** | **6,000,000** | **10,000,000** |
| Reagents | 2,400,000 | 5,100,000 |
| Power | 2,300,000 | 2,500,000 |
| Maintenance | 1,200,000 | 2,300,000 |
| Labour* | - | - |

*For the purposes of this analysis it has been assumed that the Labour requirements are equal.

**DISCUSSION**

There are four commercially proven common, pre-treatment options for refractory gold ores: roasting; pressure oxidation; bio-oxidation; and ultrafine grinding, of which Albion Process™ is one application. For the purposes of this direct comparison only POx is being evaluated against Albion Process™ as POx is currently the process route often employed for refractory ores due to environmental permitting. In some countries it is difficult to obtain approvals to build a roaster circuit and in other countries arsenic materials can only be handled by pressure oxidation. Pressure oxidation for high arsenic ores and concentrates has been around for more than 30 years and can be said to be a mature technology.

The advantage of pressure oxidation is a higher oxidation (near complete breakdown of sulphides) allowing locked gold to be liberated and hence maximises gold recovery from any refractory ore or concentrate. Pressure oxidation can be used on a very wide range of feed materials from low sulphide whole ores to high grade flotation concentrates. Additionally, depending on acid levels and the iron to arsenic ratio, almost all of the arsenic forms a stable ferric arsenic complex currently considered to be environmentally safe. Ores and concentrates with significant copper levels can be treated for both gold and copper recovery; a significant portion of the copper in the ore is solubilised and available for recovery by precipitation of the $Cu^{++}$ ion in a downstream process. For the purpose of this evaluation, only a high grade, relatively clean concentrate is being compared, as Albion Process™ is not suitable for whole ore processing due to the high cost of grinding ore.

The disadvantages of pressure oxidation are the high capital cost for specialised equipment and the requirement for a more "technical" workforce. Pressure oxidation may also not be suitable for ores and concentrates containing high amounts of silver. Silver often reacts to form silver-jarosite which is resistant to cyanide leaching. Therefore, silver recovery may be lower than other treatment methods. If not well controlled, basic iron sulphate and iron jarosite (instead of hematite) can also form, making downstream processing difficult with the added possibility of some acid and metal release into the environment from tailings ponds. Basic iron sulphate causes problems in the cyanidation process mainly due to the fact that under certain conditions the compound breaks down, releasing acid.

As identified in the cost comparison above, the Albion Process™ has a lower capital intensity and lower operating cost than the traditional POx process. The simplicity of the Albion Process™ flowsheet results in a smaller number of unit operations, simple plant layout, moderate operating temperature and atmospheric leach conditions. In addition to the cost advantages of the Albion Process™, the chemistry associated with the process presents a number of advantages. The advantages associated with the Albion Process™ chemistry include; fixing impurities in an inert residue with limestone with no production of sulphur dioxide, fixing of arsenic as ferric arsenate and the continual neutralisation of iron and acid in the process.

Less tangible advantages of the Albion Process™ are based around the relatively simple unit operations. including the requirements for a less technically skilled workforce to operate and maintain the plant. In addition, the advantage of a fast ramp-up of the circuit to nameplate capacity avoids costly delays which have the potential to damage the business case.

During a project's initial development all ores and concentrates need to go through a rigorous test work program. In this particular instance the Albion Process™ is the preferred process option both from a capital and operating cost basis. However, gold recovery is higher with POx than the Albion Process™. In this particular case study, high gold leach extractions were achieved (93%) with comparatively low oxidation (76% oxidation) compared to POx. It must be said that this performance is specific to the GPM Gold plant ore and concentrate; therefore, there is a need for a thorough metallurgical test program to fully evaluate the process options for other ores and concentrates.

## SUMMARY AND CONCLUSIONS

Each refractory gold process selection is unique and should initially include the four current options of biological oxidation (BIOX), roasting, pressure oxidation and the Albion Process™. For this paper, only the latter two are considered on a comparative capital and operating cost basis. The metallurgical performance for POx has been implied. It is vital that project metallurgical process route selection be driven by adequate metallurgical testing as refractory gold ores are notoriously individual.

The Albion Process™ process exhibits a shorter project implementation time, reduced technical complexity with resultant benefits of simplification, higher utilisation and reliable metallurgical performance. The higher recovery of POx must be balanced against these other project parameters in determining the optimum project economics.

The quantifiable cost benefits and the qualitative operating and maintenance benefits of the Albion Process™ make it a viable alternative for processing refractory gold concentrates, warranting consideration in the flowsheet development for a refractory gold project.

**ACKNOWLEDGEMENTS**

It is acknowledged that there exists a considerable degree of prior knowledge and experience that has been built up and documented for gold POx and the practical application of the mature autoclave technology. Authors and contributors to this level of knowledge are recognised and thanked.

For the Albion Process™ there is now emerging public access to detailed information able to be used for industry studies and the efforts in this regard from GPM Gold, Glencore Technology and Core Resources are acknowledged.

This paper was only made possible with the active support and generous provision of information from Glencore Technology and the Albion Process™ marketer and testwork provider Core Resources. In particular, contributions were vital from Paul Voigt, Daniel Mallah, Mike Hourn and Peter Rohner.

The Denver and Brisbane teams of Jacobs collaborated to proactively work on this paper. The estimating effort from Denver is acknowledged as is the Jacobs expertise and database accessed for the POx information in particular. It should be emphasised that the theoretical POx flowsheet used in this comparative exercise requires assumptions and judgements that will not apply necessarily to a particular implemented project.

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