

Leaching of Copper Sulphides

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In the ten years from 2003 to 2013 global mine production of copper has increased by over 23% to meet demand while the weighted average head grade has dropped from 0.9 to 0.7% Cu. These divergent trends of increasing demand and declining economic grades will extend the life of many existing mines and improve the viability of marginal and/or complex copper deposits. Against that context this paper outlines hydrometallurgical copper sulphide leaching options as alternatives to the more conventional pyrometallurgical processing route of copper sulphides.

Three copper sulphide leaching and refining processes are discussed: total pressure oxidation, ferric sulphate leaching and copper chloride leaching. The effect of mineralogy on the choice of processing technology is discussed as well as some of the unit processes used. Additionally, possible benefits that a hydrometallurgical process may offer over an existing pyrometallurgical route are discussed. Subsequently, two very important aspects to the development of projects involving the leaching of copper sulphides are discussed. Finally, a number of conclusions are presented that will be useful to keep in mind when considering projects involving the leaching of copper sulphides.

INTRODUCTION

In the ten years from 2003 to 2013 global mine production of copper has increased by over 23% to meet demand while the weighted average head grade has dropped from 0.9 to 0.73% Cu (Murphy, 2014). If these divergent trends of increasing demand and declining economic grades continue, they will contribute to the extension in life of many existing mines and improve the viability of marginal and/or complex copper deposits. Against that context, this paper outlines hydrometallurgical copper sulphide leaching options as alternatives to the more conventional pyrometallurgical processing route for copper sulphides. Three copper sulphide leaching and refining processes are discussed: total pressure oxidation, ferric sulphate leaching and copper chloride leaching. Ferric sulphate leaching and copper chloride leaching are carried out at atmospheric pressure while total pressure oxidation takes place at elevated pressures.

Hydrometallurgical processing routes may be sought for a number of reasons as alternatives to more conventional pyrometallurgical processing (Dreisinger, 2006). In general, the selection of a hydrometallurgical process for use in a commercial application will require that many of the following characteristics are true of the process selected:

- The use of proven unit processes and equipment.
- High metal recovery and good product quality.
- The recovery of other valuable metals such as gold and silver can be carried out economically.
- The process is flexible in terms of the mineralogy, grade and impurity concentrations it can handle while still delivering a safe and robust operation with minimal environmental impact.

- The technology should be suitable for retrofits, e.g., the conversion of a copper heap leach, solvent extraction (SX) and electrowinning (EW) facility once the oxide and transition material is exhausted (Valkama, 2013).

Throughout this paper, 'copper sulphides' describes both mixed copper-iron sulphides, such as bornite and chalcopyrite (Cu_5FeS_4 and CuFeS_2 , respectively) as well as copper sulphides, such as chalcocite, digenite and covellite (Cu_2S , Cu_9S_5 and CuS , respectively).

LEACHING OPTIONS

Three copper sulphide leaching processes are discussed in the sections that follow. Total pressure oxidation (POX) and ferric sulphate leaching are carried out in environments that are sulphate-based while copper chloride leaching takes place in a chloride-based solution environment.

Total Pressure Oxidation

Total POX plants operated in the USA in the 1950s and, more recently, continue to operate at the First Quantum Minerals HPL plant in Solwezi, Zambia. As a result, they should now be considered proven technology (Dreisinger, 2006).

Total POX is carried out in an autoclave reactor run in a continuous manner that is designed to operate in an oxidising, acidic environment at elevated temperature and pressure. The autoclave environment consists of a complex combination of vapour, liquid and solids phases through which many of the reagents and products of the reactor chemistry transit. For this reason, the chemical reactor design of the autoclave is very important to its successful operation.

Total POX autoclaves operate in sulphate-based environments at a temperature of greater than 200°C. At these elevated temperatures, the total POX autoclave is classified as a high temperature pressure leaching process (Marsden, 2007a). The pressure range at which total POX autoclaves operate is between 30–40 atmospheres (Dreisinger, 2006). This combination of high pressure and temperature, as well as the continuous operation of the autoclave, make the mechanical design of the autoclave reactor another very important aspect to a successful total POX circuit delivery.

High-pressure oxygen gas is introduced into the autoclave in such a way as to maximise the dissolution of the gas into the solution phase. Once dissolved in the solution, oxygen reacts exothermically with sulphide minerals at the surface of the solid phase, forming sulphate ions that enter the solution phase (sulphuric acid). For this reason, dissolved oxygen (DO) levels in the aqueous phase are an important parameter in enhancing the rate of the sulphide oxidation reaction. In general, however, the solubility of oxygen in an aqueous phase reduces as the temperature increases. Due to the lower oxygen solubility at elevated temperatures, the importance of the following design requirements is enhanced:

- Oxygen dispersion in the liquid phase;
- Maintenance of the oxygen partial pressure in the vapour phase; and
- The degree to which the vapour phase is reincorporated in the slurry.

The mixing system design within the autoclave addresses the oxygen dispersion and vapour phase reincorporation design requirements. The oxygen partial pressure design requirement is managed by maintaining the autoclave pressure with the addition of pressurised oxygen gas and the regular purging of the autoclave vapour phase and subsequent analysis of the off gas.

Many of the minerals fed to a POX autoclave contain significant amounts of iron. The reactions that the iron-containing minerals undergo, as well as the form of iron that occurs in the leaching reaction mechanisms and ultimately exits the autoclave, are of particular importance to the overall process.

With sufficient DO in solution and under the total POX conditions described above, ferric sulphate leached from solid minerals in the autoclave hydrolyses with water to form preferred solid haematite crystals (Marsden, 2003). At lower temperatures and higher acidity however, the ferric sulphate in solution will tend to favour the formation of basic iron sulphate ($\text{Fe}(\text{OH})\text{SO}_4$) (Fleming, 2009).

At high-temperature pressure leaching conditions, the formation of sulphuric acid from sulphides in the ore is favoured, however at medium- and low-temperature conditions (150–165°C and >140°C, respectively) elemental sulphur formation occurs. At these temperatures, the elemental sulphur is molten and causes issues in further leaching. A high yield of elemental sulphur reduces the oxygen requirement in the autoclave reactions and, in addition, the downstream acid neutralisation (Dreisinger, 2006) if no acid sink, such as a heap leach, is available on site. For these reasons, medium- to low-temperature POX conditions may be worth considering in some copper sulphide leaching scenarios.

Simplified Flowsheet

A simplified flowsheet outlining total POX in a copper circuit is shown in Figure 1. Two points are worth noting, firstly the acid generated in the oxidation of the sulphides in the concentrate pressure leaching step and that produced in the extraction of copper from the pregnant leach solution (PLS) is available for use in a copper heap leaching unit process. In this way, an acid credit to the operating cost is derived (Dreisinger, 2006). Secondly, it is worth noting that the POX residue can be leached in an atmospheric halide leaching step to recover precious metals, such as gold and silver, that may be present in the copper concentrate. This additional step is likely to improve the economics of the circuit if there are sufficient precious metals in the concentrate.

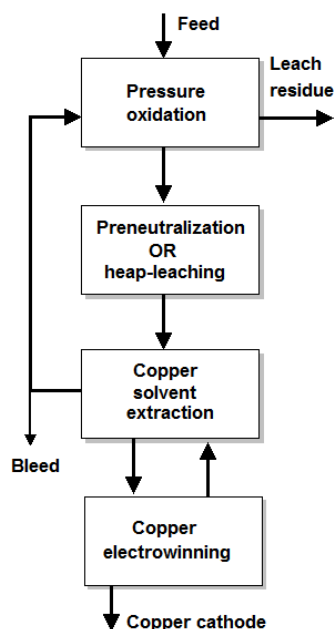


Figure 1. Simplified flowsheet indicating the integration of total POX in a copper heap leach circuit.

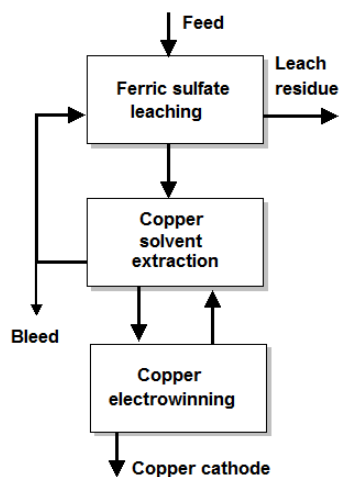


Figure 2. Simplified ferric leaching flowsheet.

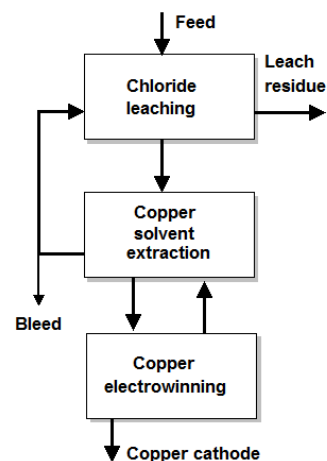
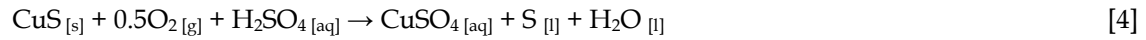
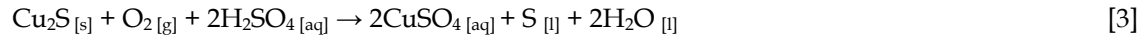
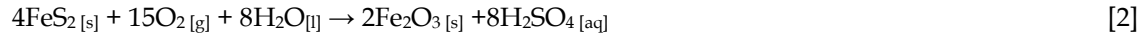
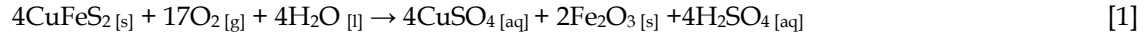


Figure 3. Copper chloride leach process.

Leaching Chemistry

As outlined earlier, the leaching chemistry that takes place within a total POX autoclave is very complex and will vary from case to case according to the mineralogy of the concentrate fed to the autoclave. However, simplified representations of the leaching of chalcocite (Cu_2S), covellite (CuS) and covellite (CuS) are presented in Equations [1] to [5].



More detailed explanations of these and other oxidation reactions are presented by Dreisinger (2006).

Ferric Sulphate Leaching

Ferric sulphate leaching of secondary sulphide ores has been successfully commercialised at the Cobre Las Cruces (CLC) and Sepon copper plants.

Cobre Las Cruces

More detail on the development of this project is outlined in the project development section of this paper. The final CLC leaching parameters defined through test work, process design, optimisation and validation are summarised in Table I.

Table I. Leaching parameters at Cobre Las Cruces.

Ore feed	165 t/h	Installed motor size	500 kW
Leach residence time	8 h	Solids concentration	500 – 550 g/L
Number of leach reactors	8	Copper leach extraction	~ 92%
Effective volume per leach reactor	350 m ³	Leach temperature	90°C
Agitation power (with oxygen)	1.4 kW/m ³	Oxygen supply	98% pure

Sepon Copper Plant

Copper at Sepon is mainly present as chalcocite with pyrite and a large component of clay mineralisation. The leach residue is subjected to flotation to recover pyrite and elemental sulphur which is subsequently fed to an oxidising autoclave. Within the autoclave, the elemental sulphur and pyrite are oxidised to form sulphuric acid and basic ferric sulphate is produced, rather than haematite as is the case in a normal high temperature total POX operation. The sulphuric acid and basic ferric sulphate are recycled to the leach step and provide the acid and strong ferric sulphate solution required in the leach. The autoclave oxidation step provides virtually all acid and ferric sulphate required for the copper leaching process (Dreisinger, 2006).

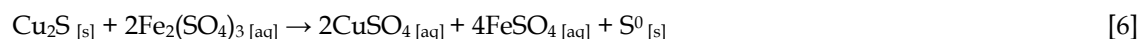
Leach reactors are operated at atmospheric pressure near the boiling point of the slurry. The leach reactions are exothermic, which allows for the preheating of the leach feed slurry with the leach discharge slurry. At Sepon, oxygen is fed to the first of four leach reactors while blower air is fed to the remainder. After leaching, the hot slurry is cooled in slurry cooling towers to ensure the controlled precipitation of gypsum after which the slurry is fed to the counter-current decantation (CCD) circuit (Keokhouns, 2006).

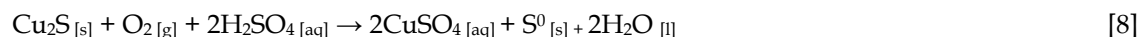
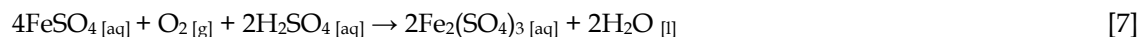
Simplified Flowsheet

A simplified ferric sulphate leaching flowsheet is presented in Figure 2.

Leaching Chemistry

The simplified chemistry of ferric sulphate leaching of chalcocite (Cu₂S) is presented in Equations [6] and [7]. Equation [8] shows the overall reaction without the ferric/ferrous intermediate mechanism.





Copper Chloride Leaching

Outotec's copper chloride leaching process is carried out in atmospheric leach reactors with cupric ions, Cu(II), in a chloride media at a pH between 2 and 2.8. The leach conditions are suitable for the leaching of all copper sulphide minerals, such as chalcopyrite, bornite, chalcocite, covellite and digenite (Valkama, 2013). These leach conditions have delivered high recoveries of copper and silver (95–98% and 93–96%, respectively) in batch tests and pilot runs. Chloride from sodium chloride enables the leaching reactions but it is not consumed in them and sulphuric acid is used as a makeup acid. Because of the nature of the leaching solution and the subsequent SX, neither chemical has stringent purity requirements. Silver and gold can be recovered also if they are present in the feed. As a result, the technology is suited to a wide variety of copper-containing feed materials.

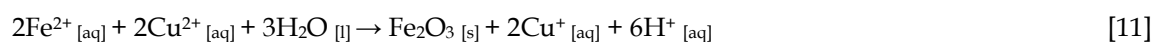
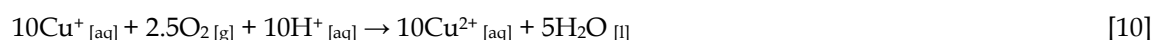
The copper leached is subsequently recovered with conventional SX-EW technology and London Metal Exchange (LME) Grade A copper cathode is produced. Pyrite, haematite and magnetite do not dissolve in the environment (Lundstrom, 2009). This offers benefits in the downstream solution purification steps and the possibility to accept a lower copper grade concentrate as feed.

Simplified Flowsheet

A simplified flowsheet outlining the copper chloride leach process is presented in Figure 3. Silver is leached together with copper and, depending on the silver content of the feed material, silver can be recovered either from the main circuit or from bleed. If gold is present, it can be recovered from the leaching residue.

Leaching Chemistry

The chemistry of the copper chloride leaching of chalcopyrite (CuFeS_2), cupric oxidation and simultaneous haematite precipitation are presented in Equations [9], [10] and [11]. Equation [12] shows the overall reaction.



Secondary copper sulphides are leached in a similar fashion. Similar to ferric sulphate leaching, this process requires acid, as opposed to POX where excess acid is produced. A small part of elemental sulphur will oxidize to sulphuric acid but the acid balance still remains negative. Most of the acid comes from SX raffinate, the same as in ferric sulphate leaching.

IMPORTANCE OF MINERALOGY

When considering the leaching of copper sulphides, it is very important to understand the mineralogy of the ore body because not all leaching options are suitable for all minerals. A very effective way to develop the required understanding of the mineralogy is to do test work on site-specific ores. It is important that this test work is done on representative samples from the ore body. In addition, it is important to understand any variability of different zones of the ore body to the leach conditions, particularly material that will be fed during the early stages of operation.

Table II outlines the response of a selection of minerals to the copper sulphide leaching conditions detailed in this paper.

Table II. High level mineralogical response to copper sulphide leaching conditions.

Mineral	Total POX leach	Ferric sulphate leach	Copper chloride leach
Chalcopyrite (CuFeS ₂)	Copper leaches Iron forms hematite Sulphur forms H ₂ SO ₄	Inert	Copper leaches Iron forms mainly haematite Sulphur forms mainly S ^o
Bornite (Cu ₅ FeS ₄)	Copper leaches Iron forms hematite Sulphur forms H ₂ SO ₄	Inert	Copper leaches Iron forms mainly haematite Sulphur forms mainly S ^o
Chalcocite (Cu ₂ S ₇)	Copper leaches Sulphur forms H ₂ SO ₄	Copper leaches Sulphur forms mainly S ^o	Copper leaches Sulphur forms mainly S ^o
Digenite (Cu ₉ S ₅)	Copper leaches Sulphur forms H ₂ SO ₄	Copper leaches Sulphur forms mainly S ^o	Copper leaches Sulphur forms mainly S ^o
Covellite (CuS)	Copper leaches Sulphur forms H ₂ SO ₄	Copper leaches Sulphur forms mainly S ^o	Copper leaches Sulphur forms mainly S ^o
Pyrite (FeS ₂)	Iron forms hematite Sulphur forms H ₂ SO ₄	Virtually inert	Inert
Hematite (Fe ₂ O ₃)	Iron forms hematite	Virtually inert	Inert
Magnetite (Fe ₃ O ₄)	Iron forms hematite	Virtually inert	Inert

The sulphuric acid from all the sulphide minerals formed in total POX will need to be consumed or neutralised elsewhere in the process. Additionally, the amount of oxygen required in the autoclave will be significantly higher than that required in the other two leaching conditions. Therefore the operating costs for the total POX option may be significantly higher than copper chloride leaching if there is a high cost for oxygen supply (electricity) and no heap leach available to neutralise the additional acid formed.

The mineralogical association of any precious metals present in the ore is also an interesting point to consider. For example, if gold is associated with pyrite it can be seen that total POX will be the most effective means to liberate it from the pyrite matrix.

DISCUSSION ON UNIT PROCESSES

The following sections introduce a selection of the key unit processes that typically form part of the overall process in the three leaching options presented in this paper.

Pressure Oxidation

The autoclave and ancillary equipment that make up the pressure oxidation unit process operate under an extreme set of conditions (temperature, pressure, corrosion, etc.). This demands that all aspects of the design and subsequent operation are particularly well understood, defined and then addressed in the delivery of the unit process.

In general, it is important to understand the life-of-mine feed to the POX circuit in order to suitably define these design parameters. For example, key variables, such as changes in the mineralogy over time, can have a dramatic effect on the amount of energy evolved during the oxidation reaction, oxygen demand and the recovery of copper. These variables impact on design considerations, such as

the selection of materials of construction, oxygen plant sizing, operator training, scale formation and steam provision.

Additionally, it is important to consider recent enhancements to the autoclave agitation system, energy and water recovery, which significantly improve the oxygen mass transfer from the gas phase into solution enhancing the oxygen utilisation. Novel energy and water recovery technology allows for further off sets in the operating costs of the unit process (Tiihonen et al., 2013). Outotec has recently developed a POX project with these features from the concept study through to detailed design and delivery for the Russian gold producer Petropavlovsk Group (Tiihonen et al., 2013).

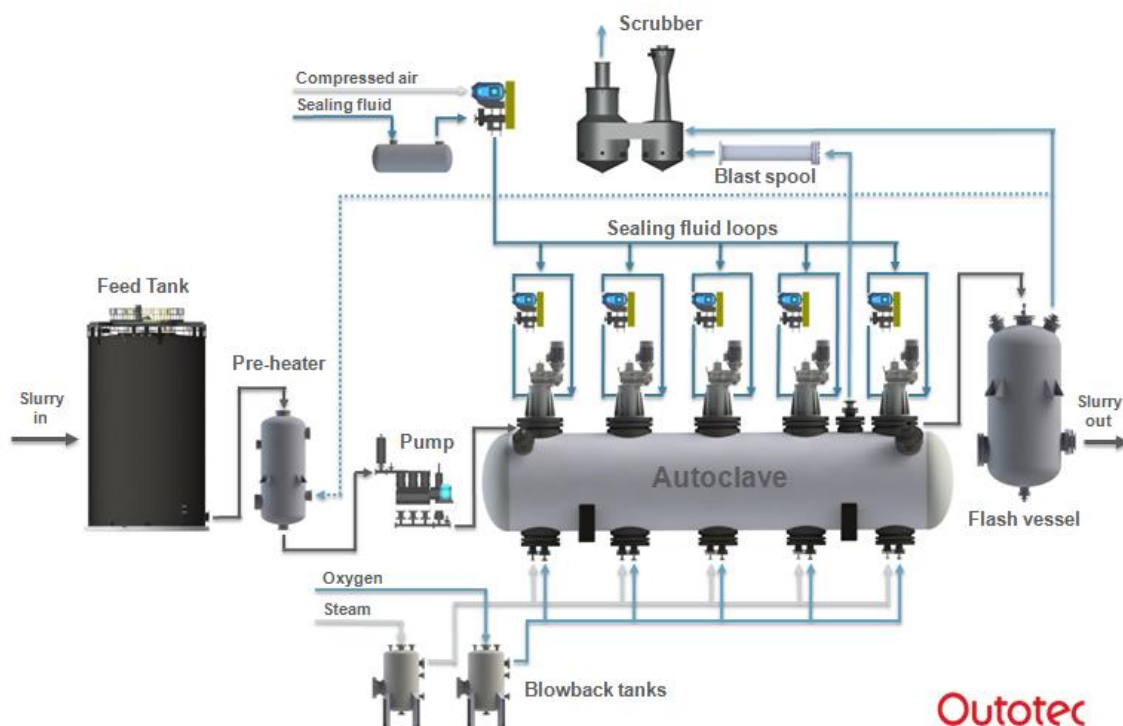


Figure 4. Typical POX autoclave delivery scope.

Atmospheric Leach

Atmospheric leaching of copper sulphides is carried out in challenging conditions of elevated temperature, low pH and high chloride ion concentrations. In addition, the reactors need to optimally cater for a three-phase reaction dynamic in which gaseous oxygen, solid copper concentrate and metal containing aqueous solution all interact.

Other very important factors to consider include the heat-balance management of the reactor because heating may be required for start-up and cooling during operation and the correct specification of the materials of construction. The demands of this environment require a technically sound evaluation by a highly skilled, experienced and therefore competent engineering team. An excellent overview of the importance of reactor design in hydrometallurgy as well as the many recent innovations available in this area is given by Latva-Kokko (2014).

Good reactor design is critical for efficient leaching, precipitation and metal recovery processes. The innovative and successful design of Cobre Las Cruces' chalcocite leaching atmospheric reactors is a typical example of this expertise. The copper recovery ratio of the OKTOP® 5000 series reactors provided a new atmospheric direct leaching process. To ensure high yields, low operating costs and the flexibility required, a scale model of the copper plant was built in the laboratory. This scale model demonstration convincingly proved the performance of the atmospheric leaching process. The design

cycle, including physical modeling, leaching and precipitation tests, fluid dynamics analysis, mechanical design, life-cycle analysis, quality control and assurance and built-in safety procedures should be considered for the optimal reactor design for each unique process.

Slurry Cooling

Slurry cooling is required after elevated-temperature leaching to aid in the operation of downstream unit processes, such as CCD and SX. For example, ineffective settling of solids in a CCD circuit is experienced if the feed to the circuit is hot and cools during the relatively long residence times in sequential thickeners. Additionally, soluble impurities, such as calcium, that enter the solution in the elevated-temperature leach of copper sulphides are problematic once the solution cools and their solubility is reduced. Slurry cooling therefore reduces the temperature of the CCD feed and allows for controlled precipitation of gypsum upstream of the SX plant.

In 2012 Chambishi plc in Zambia commissioned a slurry-cooling tower installation with a novel tower design (Hirsi et al., 2013). This makes it possible to direct hot slurry straight from leaching to the cooling tower and then perform a simultaneous solid separation for leach residue and gypsum in the thickener after the cooling tower. Efficient droplet separation lowers the emissions for the tower, which leads to less environmental impact. It can also lower plant maintenance costs because there is less corrosion to the platforms and other structures adjacent to the cooling tower. With older or dysfunctional tower designs, emissions can have a significant corrosive effect (Hirsi et al., 2013).

Solvent Extraction

In the SX unit process, the contained copper in a PLS is removed by an organic stream that contains an extractant. The extractant targets copper ions in the aqueous phase. This is referred to as extraction. The copper enters the organic phase by displacing protons in the organic phase. These protons subsequently enter the aqueous phase. This extraction reaction increases the acid concentration in the aqueous stream and the copper concentration in the organic stream that exists. The aqueous PLS stream that enters the extraction circuit of the SX circuit leaves as a high acid-containing solution and is referred to as raffinate.

Lean electrolyte with a high acid concentration from the EW tankhouse is used to strip copper from the organic phase by reversing the reactions in that took place in the extraction step. The copper enters the aqueous phase by displacing protons in the lean electrolyte. These protons subsequently enter the organic phase.

Recently, a modular SX plant offering, VSF® X, has entered the market. This uses prefabricated and easily transportable modules. This new development addresses many of the sustainability issues due to its positive impact on engineering, manufacturing, installation, operation and maintenance (Weatherseed et al., 2014). VSF® X is expected to offer a significant value proposition in that it will offer a lower capital cost and lead time, largely due to the reduced on site construction and installation requirement.

Electrowinning

LME Grade A copper is plated on cathodes from electrolyte solution in the EW unit process. This is the final chemical step in the process, with the balance of the operation focussing on materials handling of the copper cathode. EW technology is well known and delivers an efficient, productive and safe plant with optimised cathode and cell sizes, current densities, busbars and automatic handling of cathodes.

Despite this reliability, new EW innovations are available. Titanium anodes are one such example. These operate with a low cell voltage and therefore consume up to 15 % less energy than conventional lead anodes, offering significant savings to the electrical consumption of an EW plant. Republic Alternative Technologies is the world's first producer of innovative mixed metal-oxide-coated titanium anodes, which are used as an alternative to conventional lead anodes in EW operations. They

are suitable for the refining of copper, zinc and other metals. In addition, titanium anodes eliminate the requirement to clean cells periodically and therefore remove the health hazard presented by handling lead flakes in normal lead anode operations. These titanium anodes are currently used in industrial copper EW plants in Arizona, New Mexico and South America.

A Tankhouse Information Management System (TIMS) is a new and modern data collection, reporting and management system suitable for all tankhouse operations. It integrates process control, material handling machines and cell-monitoring systems, providing powerful and on-line material, quality and efficiency tracking features, together with easy access to data. Significant benefits are gained in increasing the energy efficiency and product quality as well as improving maintenance and safety using such TIMS systems.

Cementation, Precipitation and Neutralisation

As an alternative to conventional SX-EW plants that produce copper cathode, it may be necessary or desirable to produce a metal precipitate or cement metal from solution. The delivery of a sulfide precipitation process to the Pueblo Viejo gold mine in the Dominican Republic is one such example.

The ore treated in the Pueblo Viejo gold leaching process contains copper, which is removed from the process as copper sulphide. This application utilizes high-quality reactor technology and Paques THIOTEQ® bioprocess as a hydrogen sulfide source. The scope of delivery included engineering, proprietary and process equipment, instrumentation and automation, as well as supervisory services and spare parts. The plant was supplied as prefabricated skid-mounted units, minimizing the amount of site work and ensuring fast track implementation. The units were pre-tested in workshops to ensure safety and first commissioned on site in 2013.

HYDROMETALLURGICAL PROCESSING BENEFITS

The following sections outline benefits that may be possible if a hydrometallurgical process is selected over the sale of concentrate to an existing pyrometallurgical copper smelter. It is important to note that each ore body will bring with it a unique set of characteristics that will determine whether any of these benefits can be realised in practice.

Grade vs. Recovery

In general, the onsite hydrometallurgical processing of copper concentrates will allow for a re-evaluation of the optimal point to operate the flotation circuit in terms of the flotation grade vs. recovery curve. Removing or relaxing the need to reduce concentrate mass for subsequent transportation or to meet higher copper or sulphur grades in the concentrate can allow for a higher overall copper recovery to be achieved. This will, in turn, enhance the revenue that can be generated due to a higher copper production per ton of ore processed.

Impurities

New copper sulphide leaching processes can be designed to have a greater tolerance to impurities such as As, Sb, Bi, and halides than existing copper concentrate smelters are able to process. This will allow for difficult or complex deposits that contain relatively high levels of such impurities to be hydrometallurgically processed when the economics of the specific case is favourable.

Use of Saline Water

The supply of fresh water is limited in some regions which drives the related costs for alternative sources of water up. Copper chloride leaching can make use of some saline water sources, reducing the need for sodium chloride make-up. In addition, this flexibility can reduce the raw water demand of the overall process.

Sulphur

In the processes outlined in this paper, sulphur exits the process as either elemental sulphur or as neutralised solids, such as gypsum. In both of these forms, the sulphur compound is a solid and therefore a relatively dense product. In this form, it is relatively cost effective to handle when compared with gaseous forms such as SO_2 or SO_3 generated in smelting. Gaseous sulphur compounds at elevated temperatures require large ducting, gas cleaning and sulphuric acid plant equipment to capture the sulphur and limit the emission of this pollutant.

Value Addition in Local Economy

Several developing countries, particularly in Africa, have adopted policies that target downstream value addition to their economies. This typically involves a range of activities, including large-scale capital intensive activities, such as refining, as well as labour-intensive activities, such as metal fabrication and equipment manufacture (Department of Mineral Resources South Africa, 2011). The production of a refined copper product, via the leaching processes mentioned in this paper, rather than the export of copper concentrate fits well with many of these policies. As a result, the policies are expected to enhance the case for the development of copper sulphide leaching projects in regions where they are adopted by governments, particularly in Africa.

PROJECT DEVELOPMENT

The activities of a company can be seen as a collection or a succession of projects (Crundwell, 2008). Therefore it is important to understand the objectives and context in which a company developing a project is operating in, specifically one involving the leaching of copper sulphides. Two very important aspects to the development of projects involving the leaching of copper sulphides are presented in the sections that follow. Firstly a typical project schedule is outlined. Subsequently the importance of test work and piloting is outlined.

Typical Project Schedule

Outotec played an integral role in the flowsheet development, technology and equipment supply at CLC. As a result, the development schedule for the project is the example presented for a typical project schedule to the industrial application of a copper sulphide leaching process. The timing of an actual project will be impacted by such factors as the complexity of the ore, project ownership changes, metal prices and market conditions, as well as others.

In 2002 research work was done to re-estimate the investment costs required for an atmospheric leach rather than a pressure leach process for the CLC project. From 2004 to 2005, the leaching process was further developed before basic engineering (similar to a definitive feasibility study level of detail) was completed in 2006. The implementation phase followed and the production of first copper was achieved in June 2009.

An iterative design to the leach circuit was followed during this development cycle. This cycle started with the best estimation of an industrial-scale atmospheric leaching reactor with design criterion for kinetics selected based on literature and past experience. The configuration for the leach circuit was designed based on physical modelling.

The next step in the iterative cycle was to carry out a technical validation of the industrial-scale leach circuit. This was done by scaling down the reactor configuration to a pilot scale and then running a set of pilot tests. These tests proved that the selection of atmospheric leaching for the CLC project was valid and allowed the project to advance into the basic engineering or definitive feasibility stage.

During the basic engineering phase, optimisation of the leach reactor configuration was undertaken as the kinetic leaching tests proved that the assumed study phase design criterion were not ideal for the CLC ore body. The optimal reactor configuration was defined by physical modeling tests. The evolved

design was then validated by chemical laboratory tests. The scalability of the evolved reactor design was then verified by computer simulation of the reactor fluid dynamics.

The detailed mechanical design was then carried out by the reactor team and included a structural analysis using finite element analysis (FEA) and lead to the firm pricing of the design. Life-cycle cost analyses were then used to verify the viability of the original design, evolved design and third-party design criterion. A peer review was carried out by a committee of third-party consultants and professors who confirmed the reactor design by validating the computational fluid dynamics (CFD) with physical modeling and by conducting an economical evaluation of the design criterion.

Test Work and Piloting

To develop a hydrometallurgical project such as the leaching of copper sulphides, a detailed business plan over the life of the operation is required. This will need to outline the timing of various cash flows in order to estimate the value that will be generated by implementing the project. These cash flows can be split into three broad categories, namely revenue, capital costs and operating costs. It is worth noting that all three of these cash flow categories are intimately linked to the results generated from the metallurgical test work and piloting carried out on the ore body. For these reasons, the quality and extent of the test work and piloting carried out in the development of the business plan should be as detailed and well documented as can be afforded. Results that are not favorable or that highlight issues in the operation obtained during this early stage of development add significant value in that they ensure that the risk of unexpected variations in the cash flow in the future is reduced.

A detailed and thorough test work and pilot campaign is a critical aspect to the successful development of most mining and metal projects but even more so in the case of complex hydrometallurgical projects that would include the leaching of copper sulphides.

CONCLUSIONS

The conclusions that can be drawn from the contents of this paper are listed below:

- Hydrometallurgical leaching of copper sulphides is an option to consider, regardless of the feed material.
- Several developing countries have adopted policies that target downstream value addition to their economies. The production of a refined copper product is a good fit and is therefore expected to enhance the case for the development of copper sulphide leaching projects, particularly in Africa.
- The local acid market can be taken into account when identifying hydrometallurgical options for the leaching of copper sulphides because sulphur in the feed can either be converted into sulphuric acid or elemental sulphur.
- When considering the leaching of copper sulphides, it is very important to understand the mineralogy of the ore body because not all leaching options are suitable for all minerals.
- The mineralogical association of any precious metals present in the ore is an interesting point to consider.
- There are no novel unit processes required in the production of copper cathode via the leaching of copper sulphides.
- It is likely to take a number of years to successfully develop a project that involves the leaching of copper sulphides.
- There are many critical steps to developing a successful project involving the leaching of copper sulphides. Such a project would require world-class research and process development based on sound test work and piloting. The delivery of such a project will be further underpinned by the delivery of well established and proven unit processes from reputable and experienced suppliers.

REFERENCES

- Crundwell, F. (2008). *Finance for Engineers: Evaluation and Funding of Capital Projects*. Springer-Verlag, London.
- Department of Mineral Resources South Africa (2011). A beneficiation strategy for the minerals industry of South Africa. [http://www.gov.za/sites/www.gov.za/files/Beneficiation%20Strategy%20June%202011%20final%20\(3\)_0.pdf](http://www.gov.za/sites/www.gov.za/files/Beneficiation%20Strategy%20June%202011%20final%20(3)_0.pdf).
- Dreisinger, D. (2006). Copper leaching from primary sulfides: Options for biological and chemical extraction of copper. *Hydrometallurgy*, 83, 10–20.
- Fleming, C. (2009). Basic iron sulphate—a potential killer for pressure oxidation processing of refractory gold concentrates if not handled appropriately. SGS Minerals Services, Technical Paper 2009–06.
- Hirsi, T., Salonen P., and Vaarno J. (2013). Outotec® cooling towers provide cooling efficiency and low emissions in gypsum removal in SX plants. *Proceedings Base Metals Conference 2013*. Southern African Institute of Mining and Metallurgy, Johannesburg. pp. 65–74.
- Keokhounsy, S., Moore, T., and Liu, M., (2006). Hydromet at Sepon. *Proceedings of ALTA Copper Conference*. ALTA Metallurgical Services, Melbourne.
- Latva-Kokko, M., Hirsi, T., Lindgren, M., and Ritasalo, T., (2014). Influence of reactor design to process performance in hydrometallurgical applications. *Proceedings Hydrometallurgy 2014: Volume II*. Canadian Institute of Mining, Metallurgy and Petroleum, Montreal. pp. 3–13.
- Lundstrom, M., Liipo, J., Karonen, J., Aromaa, J., (2009). Dissolution of six sulfide concentrates in the Hydrocopper® environment. *Proceedings Base Metals Conference 2009*. Southern African Institute of Mining and Metallurgy, Johannesburg. pp. 127–138.
- Marsden, J. and Brewer, R. (2003). Hydrometallurgical processing of copper concentrates by Phelps Dodge at the Bagdad mine in Arizona. *Proceedings ALTA Copper Conference*. ALTA Metallurgical Services, Melbourne.
- Marsden, J., Wilmot, J., and Hazen, N., (2007a). Medium-temperature pressure leaching of copper concentrates Part I: Chemistry and initial process development. *Minerals & Metallurgical Processing*, 24 (4), 193–204.
- Marsden, J., Wilmot, J., and Hazen, N., (2007b). Medium-temperature pressure leaching of copper concentrates Part II: Development of direct electrowinning and an acid-autogenous process. *Minerals & Metallurgical Processing*, 24 (4), 205–217.
- Marsden, J., Wilmot, J., and Mathern, D., (2007c). Medium-temperature pressure leaching of copper concentrates Part III: Commercial demonstration at Bagdad, Arizona. *Minerals & Metallurgical Processing*, 24 (4), 218–225.
- Marsden, J., Wilmot, J., and Smith, R., (2007d). Medium-temperature pressure leaching of copper concentrates Part IV: Application at Morenci, Arizona. *Minerals & Metallurgical Processing*, 24 (4), 226–236.
- Murphy, K. (2014). Strategic Report-Copper Production Pipeline, 2014: Mine Development and Production, 2004–19. SNL Metals & Mining.
- Outotec (2014). Outotec acquires premium coated titanium anode business of Republic Alternative Technologies. <http://www.outotec.com/en/Media/News/2014/Outotec-acquires-premium-coated-titanium-anode-business-of-Republic-Alternative-Technologies-Inc/>.
- Tiihonen, J., Haakana, T., and O’Callaghan, J., (2013). Outotec pressure oxidation—more out of sulfide ore. *Proceedings World Gold Conference*. The Australasian Institute of Mining and Metallurgy (The AusIMM), the Southern African Institute of Mining and Metallurgy (SAIMM) and the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), Queensland. pp. 197–205.
- Valkama, K. and Karonen, J. (2013). Outotec’s chloride based process for production of copper cathode from primary copper sulphide concentrates. *Proceedings Copper 2013*. Gecamine, Santiago. pp. 285–295.
- Weatherseed, M., Matinheikki, J., Saario, R., and Fredriksson, H., (2014). Modular mixer-settlers for SX-plant sustainability. *Proceedings ALTA Copper Conference*. ALTA Metallurgical Services, Melbourne.