

# Copper hydrometallurgy—current status, preliminary economics, future direction and positioning versus smelting<sup>①</sup>

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**Abstract:** The heap leaching of oxide copper ores with copper cathode recovery by solvent extraction and electrowinning is now well established as a low-cost method of copper recovery. This technology has recently been applied successfully to mixed oxide and chalcocite ores, notably in Chile at Cerro Colorado, Quebrada Blanca and Zaldivar. Currently, there are significant development efforts underway to try to extend heap leaching to chalcopyrite ores. The success of heap leaching/SX/EW has also led to a revival in the development of hydrometallurgical processes to recover copper from chalcopyrite and other copper concentrates. The current status of copper hydrometallurgy is reviewed and the most commercially attractive potential applications are explored. The advantages and disadvantages of the hydrometallurgical treatment of chalcopyrite concentrates and its preliminary economics are compared with those for the current best practices in copper smelting and refining.

**Key words:** copper hydrometallurgy; heap leaching/SX/EW; copper oxide ore; copper sulfide ore

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## 1 INTRODUCTION

Heap leaching of oxide copper ores with copper cathode recovery by SX/EW is now well established as a low-cost method of copper recovery. This technology has more recently been applied successfully to mixed oxide and chalcocite ores, notably in Chile at Cerro Colorado, Quebrada Blanca and Zaldivar. Currently, there are significant development efforts underway to try to extend heap leaching to chalcopyrite ores. The success of heap leaching/SX/EW has also led to a revival in the development of a second generation of hydrometallurgical processes to recover copper from chalcopyrite concentrates.

Meanwhile, the traditional copper smelting and refining process has continued to improve and expand to meet the ever growing demand for copper. Several smelters now smelt over one million mtpy of copper concentrates in a single smelting vessel, fixing over 99% of the SO<sub>2</sub> and producing over 300 000 mtpy Cu cathodes in automated electrowinning refineries. This has led to a steady decrease in the cash operating costs with the most efficient large smelter/refinery operations having costs below \$ US0.15/lb(Cu).

Against this background, this paper will provide the follows.

1) An overview of the status of copper hy-

drometallurgy both for ores and concentrates.

2) A techno-economic comparison of hydrometallurgical processes versus smelting/refining.

3) The most likely future applications for hydrometallurgical copper processes.

## 2 OVERVIEW OF HEAP LEACHING/SX/EW

Currently about 15% of the world copper production is produced from heap leaching of oxide copper and, more recently chalcocite ores. Most of these operations are in Chile, Arizona and Australia. Typical cash operating costs for mine/heap leaching/SX/EW operations are in the range of \$ US 0.40–0.55/lb(Cu), depending on ore grade, mining costs, Cu recovery, acid requirements, and power costs.

For operations in the 40 000 to 200 000 mtpy Cu range, total capital costs vary between about \$ US 4 000–5 000/(a•t)(Cu), with the higher level being more typical of the secondary copper operations. The capital costs for heap leaching/SX/EW are split roughly a third each for open-pit mining, ore crushing and heap construction, solution handling, solvent extraction and electrowinning.

For oxide ores, Cu recoveries are typically in the range of 75%–80% within 50–100 d. On-off heaps are now also used in the leaching of oxide ores as well

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as sulphide ores rather than the original permanent heaps. A secondary sulphide heap leach requires air injection into the heap to promote bacterial oxidation and leaching rates are much slower and less predictable with leach times typically in the range of 250 – 600 d to achieve 70% – 80% Cu extraction. A breakdown of direct cash operating costs for a large efficient 0.6% Cu oxide heap leach operation with 80% Cu recovery is given in Table 1.

**Table 1** Typical heap leaching/SX/EW costs

Area	Unit consumption	Unit cost/ (\$ US•t <sup>-1</sup> )	Cash cost/ (cents US•lb <sup>-1</sup> ) (Cu)
Mining	3t/ t(ore)	0.69(mined)	17.0
Crushing & heaps		0.6(ore)	5.7
Acid	10 kg/ t(ore)	50(acid)	4.7
SX/EW		220(Cu)	10.0
G & A		60(Cu)	2.7
Total direct cash costs			40.1

The low capital and operating costs of heap leaching/SX/EW operations together with the relatively simple operation and the direct production of cathode copper close to the mine site make the economics of the process very attractive. This has resulted in the initiation of research efforts to develop a heap leach for chalcopyrite ores that have traditionally been recovered by flotation followed by smelting and electrorefining. Chalcopyrite is much more difficult to leach than chalcocite and other secondary copper minerals, as shown in Table 2. Based on the experience with secondary sulphide heap leaching, to make chalcopyrite heap leaching viable will require the development of a high-temperature heap operation to obtain acceptable Cu recoveries in a reasonable leach time. The issues of managing acid and iron generation are further complexities that need resolving.

Newmont have demonstrated that high-temperature heaps are feasible for refractory gold ore oxidation. Another interesting development is the use of high chloride and other lixiviants in heap leaching. Several oxide heap leach operations, such as Michilla and Lomas Bayas, have naturally high levels of chloride and nitrate in their solutions. Antofagasta Minerals has patented a chloride-enhanced heap leach process called "Cuproclor" that uses NaCl or CaCl<sub>2</sub> additions to generate the lixiviant. It will be only a matter of time before chalcopyrite heap leaching becomes a commercial reality but it is unlikely that such a development will make the treatment of very low-grade chalcopyrite ores (< 0.5% Cu) economic.

**Table 2** Solubilities of pure sulphide copper minerals in acidic Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> solution<sup>[1]</sup>

Mineral	Size/ μm	Solubility/ %	Leach time/ d	Temperature/ °C
Chalcocite	75 – 150	50	1	35
	75 – 150	50	8	23
	75 – 150	95	8	50
Bornite	75 – 150	45	5	23
	75 – 150	85	3	50
Covellite	75 – 150	35	11	35
	75 – 150	70	50	50
Chalcopyrite	75 – 150	2	43	20
	< 40	39	57	20
	< 40	44	14	50
Enargite	75 – 150	3	60	35
	< 75	5	60	35

### 3 OVERVIEW OF CURRENT STATUS OF HYDROMETALLURGICAL PROCESSES TO TREAT CHALCOPYRITE

The first generation of copper hydrometallurgical processes were developed in the 1970's and, despite reasonable technical success, they did not prove viable economically. Since then the success of heap leaching with the commercial development of very efficient solvent extraction and electrowinning technology has led to renewed interest in this area in the 1990's. A host of new innovative copper hydrometallurgical processes have been piloted and two of the new processes: BHP Billiton's BioCop and Placer Dome's pressure leach process, will begin operation on a large demonstration plant scale (15 – 20 000 t/a (Cu)) in 2003.

The impetus for these developments have come principally for the desire to develop a viable alternative to copper smelting and to resolve its perceived drawbacks, namely SO<sub>2</sub> emissions, sulphuric acid market saturation, high capital cost and impurity limitations (As, Sb, Bi).

The perceived advantages for the development of the new copper hydrometallurgical processes are as follows.

1) Elimination of SO<sub>2</sub> emissions and a sulphur product, i. e. elemental sulphur or gypsum, other than sulphuric acid.

2) Ability to handle lower grade concentrates as well as higher levels of impurities, i. e. more effective for treating complex concentrate.

3) Lower capital cost, especially at a smaller scale than smelters.

Peter<sup>[2]</sup>, Burkin<sup>[3]</sup>, Dreisinger<sup>[4]</sup>, Lunt<sup>[5]</sup> and Jansen<sup>[6]</sup> have all made detailed reviews for the hydrometallurgical treatment of chalcopyrite concentrates. The objective of this paper is not an exhaustive review but to review the past commercial copper hydrometallurgical plant history and to highlight the current and most promising new process developments.

### 3.1 Sulphate processes

The processes based on the sulphate medium and generally using oxygen as the oxidant are the most established technology for copper leaching. The main sulphate processes are listed in Table 3. It is generally necessary to use pressure leaching at high-temperatures (150 – 225 °C) to achieve the rapid leaching rates (1 – 2 h). Fine grinding to less than 20 µm is also effective at increasing leach kinetics at lower temperatures. The atmospheric leaching processes with fine grinding require 12 – 24 h for high Cu extraction. The biological leaching processes typically require several days to achieve high Cu extraction. In almost all processes, copper is recovered using the well-proven SX/EW combination. Precious metals recovery is a significant issue with most hydrometallurgical processes. Gold recovery from total oxidation leach residues by cyanidation is high but silver recovery is more difficult due to the formation of argentojarosite. A lime-boil or other step is typically required for high silver recovery. Precious metal recovery from the sulphur-containing leach residues produced by partial oxidation processes is much more difficult.

#### 3.1.1 High temperature leaching process

The Placer Dome process, also called total pressure oxidation process<sup>[7]</sup>, used the same conditions successfully applied in the gold industry. In this process, copper sulphide minerals are decomposed by high temperature oxidation conditions (220 °C), re-

sulting in rapid and complete copper leaching accompanied by hydrolytic precipitation of iron, mainly as hematite and impurities. The features of the process are as follows.

- 1) High copper extraction and fast leaching kinetics without fine grinding.
- 2) Precious metal can be recovered by cyanidation of leaching residue.
- 3) Oxygen consumption is high because all the sulphur is converted to sulphate.
- 4) High lime consumption for acidic bleed solution neutralization unless the acidic solutions are used for heap leaching, as planned by Phelps Dodge.

A demonstration plant for this process treating 136 t/d of concentrate to produce about 16 000 t/a of copper cathode via conventional SX/EW has been constructed at Bagdad, Arizona, US by Phelps Dodge. The plant has apparently started up successfully in March 2003.

#### 3.1.2 Processes using fine grinding

The processes with using fine grinding are the Activox and Nenatech processes<sup>[8, 9]</sup>. The particle size of concentrate into leaching is less than 20 µm after ultrafine grinding. The features of these processes include the follows.

- 1) Leaching temperature in these process is lower than sulphur melting temperature of 119 °C.
- 2) Element sulphur formed in the processes remains in the leaching residue. This leads to the difficulty to recover precious metals from leaching residue.
- 3) Some sulphate is produced that is precipitated as gypsum.
- 4) Iron precipitation is as goethite and jarosite.

The Activox leaching temperature is around 110 °C and oxygen pressure is 1 000 kPa. The Nenatech process uses atmospheric pressure and temperatures below 100 °C. The main reaction path is proposed on

**Table 3** New sulphate processes for chalcopyrite concentrate leaching

Process	Leach pressure	Sulphur product	Proposed mechanism	Level of development	Note
Activox	Low	S <sup>0</sup> , SO <sub>4</sub> <sup>2-</sup>	Direct	Laboratory	Fine grinding
Nenatech	Atmospheric	S <sup>0</sup> , SO <sub>4</sub> <sup>2-</sup>	Direct	Laboratory	Fine grinding
Dynatec	Pressure( medium)	S <sup>0</sup>	Direct	Laboratory	With coal
AAC/ UBC	Pressure( medium)	S <sup>0</sup>	Direct	Pilot plant( Planed)	With surfactant
Placer Dome process	Pressure( high)	SO <sub>4</sub> <sup>2-</sup>	Direct	Demo. Plant started in 2003	High temperature
Biocop	Atmospheric	SO <sub>4</sub> <sup>2-</sup>	Indirect	Commercial( underway)	Bacterial
Bactech/ Mintek	Atmospheric	SO <sub>4</sub> <sup>2-</sup> , S <sup>0</sup>	Indirect	Demo. Plant	Bacterial
Geocoat	Atmospheric	SO <sub>4</sub> <sup>2-</sup>	Indirect	Pilot plant	Bacterial

the indirect oxidation mechanism with ferric ion.

### 3.1.3 Processes using surfactants/ additives

The most well-known process in this category is the Dynatec process using coal as the additive<sup>[10]</sup>. This process is based on the well-proven Dynatec zinc leach process. The concentrate is ground to about 30 – 50 µm and oxidized under medium temperature (150 °C for chalcopyrite). Sulphur reports largely as element sulphur to the leach residue with about 25% of the sulphur reporting as sulphate. The leach residue is floated to recover a sulphide fraction for recycle to the leach circuit and elemental sulphur is recovered by melting and hot filtration. The non-sulphidic residue is treated for gold and silver recovery by cyanidation. A lime boil is usually required for high silver recovery. Although pyrite is largely unreacted in the leach it builds up in the recirculating sulphide fraction and is essentially totally oxidized. Iron is precipitated as hematite and jarosite.

Anglo American Corporation and UBC are developing a variant of the Dynatec and Activox processes, in which the typical zinc pressure leach surfactants are added to disperse the molten sulphur. The feed is also finely ground to less than 20 µm. The leaching temperature is 150 °C. A pilot plant program is underway at the AARL facilities in South Africa.

### 3.1.4 Bacterial leaching

The discovery of the association of bacteria with acid mine drainage was firstly reported in 1947<sup>[11]</sup>. The industrial scale application of copper bioleaching can be attributed to the Kennecott Copper Corporation<sup>[12]</sup>. In the past decade, copper bioleaching have been extensively applied. The commercial performance records of secondary copper bioleaching operations and dump leaching of run-marginal grade run-of-mine copper bearing rock. The main bacteria involved in the copper sulphide minerals leaching and the treatment of other sulphide minerals include the follows.

1) Operating in low temperature (20 – 40 °C): *thiobacillus ferrooxidans*; *thiobacillus thiooxidans*; *leptospirillum ferrooxidans*.

2) Operating in medium temperature (40 – 55 °C): *Moderate thermophiles*.

3) Operating in high temperature (55 – 85 °C): *Extreme thermophiles*.

The bacteria employed widely in bioleaching or biooxidation is *thiobacillus ferrooxidans*. With further technical development, *moderate thermophiles* and *extreme thermophiles* will be applicable for extraction of copper in confined dump and in situ environment.

The BioCop process developed by BHP Billiton is

the leading bioleaching process for copper concentrate. In the process, *mesophiles* (at 42 – 45 °C) and/ or *thermophiles* (at 70 – 80 °C) are used for secondary sulphide copper leaching and chalcopyrite leaching, respectively. Pre-leaching ahead of oxidation leaching is helpful for copper recovery when treating secondary sulphide copper, but, pre-leaching has little effect on chalcopyrite leaching. Sulphur is completely oxidized to sulphate. The oxygen consumption is high in this process due to the complete sulphur oxidation.

Alliance Copper (BHP Billiton and Codelco) are building a semi-commercial demonstration plant located near the Chuquicamata mine in north Chile. The plant is designed to produce about 20 000 t/a Cu. It is scheduled to start up before the end of 2003.

Bactech/ Mintek has also developed a viable bioleaching process for various copper concentrates<sup>[13]</sup>. The flowsheet consists of moderate grind, two-stage ferric leaching with air and ferric regeneration with air. For chalcocite concentrate, mesophile at 36 – 40 °C is used and the leaching and ferrous biooxidation are carried out in the same tank. For chalcopyrite concentrate, moderate to *extreme thermophiles* at 40 – 50 °C and 70 °C is respectively used and ferrous biooxidation is done in separate tank. The sulphur is converted to element sulphur and sulphate, the sulphate is precipitated from a bleed stream as gypsum soluble iron is precipitated as hydronium jarosite. Pyrite is not attacked. Precious metals are recovered from leaching residue with cyanidation.

Bactech and Mintek have jointly developed their tank bioleaching process up to demonstration plant level at the Peñoles operation at Monterrey, Mexico. The plant is designed to produce 500 kg/d of cathode copper. A 25 000 t/a copper/ zinc commercial plant at Peñoles is under study.

Geocoat is an alternative approach to bioleaching. The process is being developed by GeoBiotics. The process involves the coating of concentrates onto a suitable substrate, usually barren rock, then stacking the coated material in a conventional heap fashion. The heap is irrigated with acidic solutions, containing iron and nutrients, while low pressure ambient air is applied at the heap base.

## 3.2 Sulphate/ chloride processes

Chloride additions to sulphate leaching improve the leach kinetics and allow lower temperature leaching. The main copper sulphate/ chloride leaching processes are shown in Table 4. In these processes, sulphur is oxidized to element sulphur, and copper is recovered by SX/ EW.



**Table 4** Sulphate/ chloride processes

Process	Lixiviant system	Reagent	Leach ambient	Sulphur product	Level of development
Noranda Antler.	HCl-CuCl <sub>2</sub> -CuSO <sub>4</sub>	O <sub>2</sub> , MnO <sub>2</sub>	Pressure	S	Laboratory
BHAS process	H <sub>2</sub> SO <sub>4</sub> -Cl	O <sub>2</sub> , NaCl	Atmosphere	S	Commercial (for matte)
CESL process	H <sub>2</sub> SO <sub>4</sub> -Cl	O <sub>2</sub> , NaCl	Pressure	S	Demo. plant

### 3.2.1 Noranda Antlerite process

This process was developed by Noranda in late 1970's<sup>[14]</sup> for the treatment of chalcopyrite concentrate. It is based upon the conversion of copper to antlerite, CuSO<sub>4</sub>·2Cu(OH)<sub>2</sub>. The leaching steps included: 1) conversion of chalcopyrite and other sulphide copper minerals to antlerite, hematite and element sulphur by treatment with cupric sulphate-cupric chloride solution at 135–145 °C and 140 kPa oxygen, and 2) leaching of the antlerite residue with sulphur acid at pH 2.5 to produce pregnant electrolyte for copper electrowinning.

### 3.2.2 BHAS process

The Broken Hill Associated Smelters Pty Ltd. (BHAS) in Port Pirie, Australia developed a process for treating a copper-lead sulphide matte with an oxygenated acid solution containing both sulphate and chloride<sup>[15]</sup>. This process was commissioned in 1984. In the process, copper dissolves while the lead remains in the solid residue as lead sulphate together with element sulphur which is recycled to lead smelter. During leaching, almost 100% Ag is remained in leaching residue at 15 g/L chloride, but a significant amount leached at higher chloride concentration. The addition of chloride is necessary to obtain satisfactory copper extraction. In the absence of chloride, the copper extraction was only 30% while it dramatically increased to 95% with chloride of more than 10 g/L. The process was operated commercially for many years but it is no longer operational.

### 3.2.3 CESL process

The CESL process was developed by Teck-Cominco<sup>[16]</sup>. The chemistry of the process is similar to the Noranda Antlerite process, i. e. an oxidizing pressure leach using a mix of cupric sulphate and cupric chloride at about 150 °C and 140 kPa pressure, followed by acid leaching to dissolve the antlerite. In the process, 10%–25% of the sulphur is oxidized to sulphate and the rest of sulphur is converted to elemental sulphur. Iron is precipitated as hematite.

There are two operation modes of the process. Mode A is for high copper concentrate (> 35% Cu). In this mode, sulphuric acid is added to autoclave and all copper in concentrate is precipitated as antlerite in

pressure leaching residue, which is sent in dilute sulphuric acid at pH 1.2–2.0 to dissolve most of the antlerite. Mode B is used for low-grade concentrate. In this mode, no sulphuric acid additions are required and only 15%–40% of copper is precipitated as antlerite giving pressure leach solution containing 50–55 g/L copper.

CESL has built a demonstration plant and successfully tested several different copper concentrates. As most of the other copper hydrometallurgical processes a major concern is the recovery of precious metals from leach residue containing elemental sulphur. CESL flowsheet for recovering PM's involves drying of the sulphur-containing residue, sulphur removal using an organic solvent, and pressure leaching of the residue followed by cyanidation.

## 3.3 Chloride (and bromide) processes

Chloride leaching of copper sulphide has received a great deal of attention in the past decades. Flett<sup>[17]</sup> recently reviewed the chloride hydrometallurgy for complex sulphide. The main chloride (and bromide) processes are shown in Table 5. The chloride processes have several distinct advantages over sulphate-based processes, and these include the follows.

- 1) Faster kinetics, making atmospheric leaching more practical;
- 2) Almost all the sulphides are oxidized to element sulphur;
- 3) High solubility of metals leading to smaller solution volumes in subsequent steps.

The major difficulties are as follows.

- 1) Chloride solutions need special construction materials leading to a relative high capital and maintenance costs for the plant.
- 2) Electrowinning directly from chloride solutions doesn't produce cathode copper.

Ferric chloride is the major favoured lixiviant in copper chloride leaching. In most of the chloride processes, copper is recovered by SX/EW. If copper is transferred from chloride solution to sulphate solution during SX, conventional sulphate electrowinning can be used for copper deposition. The copper can be also deposited as powders by EW of cuprous chloride solution as in the Clear process. In cuprous chloride solution, copper ions discharged at cathode are monovalent rather than divalent, and the reaction occurring at the anode is the oxidation of the cuprous ion rather than the liberation of chlorine. As a result, the energy requirement for chloride electrowinning can potentially be decreased significantly compared with sulphate EW.

Oxidative leaching in the presence of high chloride levels dissolves some silver with gold remain

**Table 5** Chloride ( and bromide) processes

Process	Lixivant system	Reagent	PM recovery	Copper recovery	Level of development
Clear	$\text{CuCl}_2^-$ , NaCl	$\text{O}_2$ , air	Au to residue, Ag to Cu	EW	Commercial (1976 - 1982)
Cymet	$\text{FeCl}_3^-$ , $\text{CuCl}_2^-$ , NaCl	$\text{H}_2$ , sand	Au to residue, Ag to solution	$\text{H}_2$ reduction	Pilot plant
Cuprex	$\text{FeCl}_3^-$ , NaCl	$\text{Cl}_2$	Au to residue, Ag to Cu	EW	Laboratory
Outokumpu	$\text{FeCl}_3^-$ , NaCl	$\text{Cl}_2$	Au to residue, Ag to Cu	EW	Pilot plant(planned)
Intec	NaCl-BrCl	Air, $\text{CaCO}_3$	Au and Ag to solution	Reduction/ precipitate/ EW	Pilot plant

ning in the leaching residue. Silver can be recovered by cementation with copper, if the copper is recovered through SX/EW. Gold recovery from the leach residue again is difficult with direct cyanidation because of elemental sulphur. Also pyrite is generally not leached significantly and any gold associated with pyrite will not be recovered.

### 3.3.1 Clear process

The Clear process was operated in a 100 mt/a copper leaching/electrowinning plant in Arizona, USA, between 1976 and 1982<sup>[18]</sup>. The concentrates were leached counter currently in two stages. The first used hot cupric chloride at atmospheric pressure to yield a cuprous chloride solution. After clarification, the pregnant leaching solution was sent to copper electrowinning. Copper was deposited as a powder in EW. The residue from the first leaching stage was leached under more aggressive conditions (145 °C and oxygen overpressure) to recover the residual copper, using ferric ion as the principal leaching agent. In the second leaching step, some of element sulphur was also oxidized to sulphate. This had to be removed by precipitation as gypsum.

The commercial operation had several major problems including gypsum fouling in the tankhouse, silver contamination of the final product and washing of the final product. The plant was closed due to economic reasons and because the product could not meet LME specifications.

### 3.3.2 Cymet process<sup>[19]</sup>

In the Cymet process, the copper sulphide concentrate were subjected to a two-stage countercurrent leach in a ferric chloride/ cupric chloride/ sodium chloride brine solution. Iron was rejected from solution as jarosites and various hydrous iron oxides during the second leach stage.

Copper was recovered by hydrogen reduction in a fluidized bed reactor after cuprous chloride crystallization. Copper product was melted to copper wirebars.

### 3.3.3 Cuprex process<sup>[20]</sup>

In this process, the copper sulphide concentrates were leached with a brine/ ferric chloride solution in two stages to produce a cupric chloride solution. Copper is extracted by solvent extraction and recovered as powder by electrowinning. Chlorine generated at the

anode was recovered and used to reoxidize the cuprous chloride generated in catholyte during electrowinning. Copper present in the reformed electrolyte is recovered by SX and recycled to stripping. The stripped brine is employed as anolyte in the diaphragm cells.

### 3.3.4 Outokumpu process (Hydocopper)<sup>[21]</sup>

Outokumpu has recently developed a new chloride leaching process called the Hydrocopper process. In this process the chalcopyrite concentrates are leached at atmospheric pressure with a cupric chloride-brine solution. Copper is recovered from the purified leach solution by precipitating cuprous oxide using caustic soda. The key reactants, caustic soda, chlorine for oxidation of the leach solution, and hydrogen to reduce the cuprous oxide to copper are all regenerated from the spent brine using modern chlor-alkali cell technology. The pure, solid copper product is melted and cast directly into shapes.

This process has been developed and patented by Outokumpu. It is claimed that the energy requirements can be reduced to about 1 300 kW • h/ t (Cu). To verify the technology, Outokumpu is constructing a pilot plant in Pori, Finland.

### 3.3.5 Intec process<sup>[22, 23]</sup>

The chemistry of Intec process is also very innovative. The main components of leaching solution are sodium chloride and bromide and the lixiviant,  $\text{Br-Cl}_2^-$ , is produced by anode reaction in a unique electrowinning cell. The leach is carried out at atmospheric pressure using air as the oxidant. The leach has 3 stages: copper is leached in stages 1 and 2 and gold leaching is leached in stage 3. Copper extractions of over 98% in about 12 h are claimed. Gold dissolved under the stage 3 leach conditions is recovered directly by activated carbon. After solid-liquid separation, the leach residue is ponded and the pregnant solution is purified in several stages. In the first all copper in solution is converted to cuprous by contact with copper powder. In the second, silver is removed from leaching solution by an amalgam process using mercury and aluminum additions. The final step is neutralization with limestone to pH 4.0 - 4.5 to precipitate the residual impurities. The dendritic copper produced from EW is washed and dried under inert atmosphere then melted and cast as copper shapes. The

process has been piloted on several concentrates. Again pyrite is not leached significantly and hence gold associated with pyrite will not be recovered.

#### 4 TECHNO ECONOMIC REVIEW OF HYDRO VERSUS PYRO PROCESSES

Despite the enormous amount of development work on copper hydrometallurgical processes over the past 30–40 years there is still no commercial process operating on chalcopyrite concentrates. There are several basic reasons for this:

1) The energy requirements for leaching and sulphate EW are much higher than those for modern smelting and electrorefining. Chloride-based processes offer the potential to reduce the energy requirements closer to smelting/refining but are more complex and do not produce cathode copper, the accepted form of copper for sale.

2) Since there are no commercial operations, capital and operating costs are not well established and are usually based on preliminary estimates that tend to underestimate real costs.

3) The technical risk in developing any new process is very high as evidenced by the long list of commercial failures of new processes both hydro and pyro.

4) Precious metal recovery, especially silver, from leach residues is difficult and recoveries uncertain, especially from sulphur-containing residues.

5) Based on the experiences with zinc plant leach residues that are only about 20% of the volume of chalcopyrite leach residues per unit of metal produced, leach residue disposal will be a major issue and will limit hydrometallurgical processes to remoter areas.

In addition to these basic issues, the copper smelting/refining industry has not been standing still and the benchmarks for competition have been steadily lowered as smelting/refining technology steadily

improves and older, more inefficient smelters are replaced by new, larger and more efficient operations, often in lower cost regions of the world. As a result average smelting/refining cash costs have continued to be reduced on a real cost basis. The largest and most efficient copper smelters have direct cash operating costs of about 10 cent US/lb(Cu). Modern copper electrorefining direct cash costs are about 3 cent US/lb(Cu). Thus the real cash operating costs that hydrometallurgical processes must now compete with, to challenge smelting/refining, are lowered every year.

Currently, the only commercial copper leaching process is the Mt. Gordon process<sup>[24]</sup> that treats chalcocite ore (8% Cu) directly. This process was built for a remarkably low capital cost of about \$ US1 700/(a•t)(Cu). After some initial problems, it also has ramped up to design capacity in less than 2 years and is now producing above design capacity at about 50 000 t/a of high grade copper cathode by ferric leaching and low pressure oxidation with ore particle size of 75–106  $\mu\text{m}$ . The total operating cost of the mine and processing plant is only about \$ US0.40/lb of cathode. The Mt. Gordon operation gives the best indication of copper hydrometallurgical process real capital and operating costs. A detailed breakdown of the Mt. Gordon cash operating costs is shown in Table 6, and that of large integrated copper smelter/refinery is listed in Table 7.

The Mt. Gordon process operating costs are about 23 cent US/lb(Cu) and are close to the process operating costs for simpler heap leaching/SX/EW operations despite the greater leach process complexity. The largest cost areas are the power for EW, reagents and autoclave maintenance. The labour costs are exceptionally low at only 8% of operating costs versus 20%–40% at typical smelter/refineries. The Mt. Gordon data supports the long-held hypothesis that copper hydrometallurgical plants should be less

**Table 6** Mt. Gordon leach plant operating costs(\$ US million)

Area	Reagent content	Labour	Power	Maint.	Other	Total	Total in \$ US/lb(Cu)	Distribution/ %
Crushing/ grinding	0.6	0.3	0.7	0.8	0.3	2.6	0.025	10.8
Leaching	1.8	0.5	1.0	2.5	0.7	6.4	0.061	26.7
SX/ EW	1.4	1.0	6.1	0.9	0.9	10.4	0.098	42.9
Tailings	2.1	0.1	0.1	0.4		2.8	0.027	11.6
Other					1.9	1.9	0.018	8.0
Total direct costs	6.0	1.9	7.8	4.6	3.8	24.1	0.229	100
Distribution/ %	25.1	8.0	32.3	19.0	15.6	100		

**Table 7** Direct cash operating cost for large integrated copper smelter/ refinery

Table 7. Direct cash operating cost for large integrated copper smelter/ refiner,						
Concentrate smelted/ (t•a <sup>-1</sup> )	Cathode copper/ (t•a <sup>-1</sup> )	Manpower	Electricity/ (kW•h•t <sup>-1</sup> ) <sup>①</sup>	Fuel/ GJ/ (GJ•t <sup>-1</sup> ) <sup>①</sup>		
1 000 000	320 000	650	1 300	9.0		
Direct cash operating costs/ (\$ US million•a <sup>-1</sup> ) (Distribution/ %)						
Manpower	Power	Fuel	Maintenance supplies	Consumables	Other	Total
25.3(27.5)	18.5(20.0)	8.9(10.0)	21.5(26.0)	12.5(16.0)	5.5(6.0)	92.2(100)
Smelting costs/ (\$ US•t <sup>-1</sup> ) <sup>②</sup>		Refining cost(\$ US•lb <sup>-1</sup> )		Total cost/ (\$ US•lb <sup>-1</sup> ) <sup>①</sup>		
70		0.03		0.13		

①—vs Cu; ②—vs concentrate

sensitive to scale than smelter/ refineries.

Mt. Gordon establishes the techno-economic feasibility of hydrometallurgical processes for treating chalcocite ores but there are relatively few high grade chalcocite ore deposits. The costs for hydrometallurgical processes treating chalcopyrite concentrates are going to be higher than for chalcocite ores. But Mt. Gordon process confirms that the potential exists to be able to build a copper hydrometallurgical plant for a lower capital cost and at a smaller scale than a copper smelter/ refinery. New copper smelter/ refineries typically cost about \$ US 3 500/ ( $a \cdot t$ ) (Cu) and require a minimum scale of 150 – 200 000 t/a (Cu) for economic operation. However, the direct cash operating costs of large, modern, efficient copper smelter/ refineries are still significantly lower than those that can be expected for copper hydrometallurgical processes.

The lower direct operating costs plus the higher copper and precious metal recoveries, typically about 98%, from smelter/ refineries will make it hard for copper hydrometallurgical processes to be compete for the custom treatment of chalcopyrite concentrates.

However, there are other important potential niche applications for copper hydrometallurgical processes, including the follows.

1) Treating copper concentrates close to the mine site that contain high levels of impurities that would incur high penalty charges at smelter/ refineries, such as As, Sb, Bi.

2) Providing Cu and acid in solution to heap leaching/ SX/ EW assets where the heap leachable ore is running out and where chalcopyrite concentrate is readily available from either the same mine or nearby sources.

## 5 CONCLUSIONS

Obviously, only a few of the multitude of new hydrometallurgical processes will become successful

commercial operations. The Placer Dome process and BioCop are leading the race at the moment with large demonstration plants starting up in 2003. The other leading contenders are the CESL and Dynatec processes. The latter has the benefit of the successful track record of its similar zinc pressure leach process. Halide-based processes, such as Intec, are technically innovative and offer the attraction of atmospheric leaching and the potential to reduce power requirements but the drawbacks are corrosion issues, complex flowsheets and a copper product is not cathode. Outokumpu's recent HydroCopper process is another unique approach that offers a 30% potential reduction in power requirements versus conventional sulphate EW and its development will be followed with interest.

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