

KEY ELEMENTS IN THE SELECTION OF SULPHIDE LEACH PROCESSES FOR COPPER CONCENTRATE LEACHING

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TABLE OF CONTENTS

1.	INTRODUCTION	1
2.	SUMMARY	2
3.	PROCESS OPTIONS	3
4.	PROCESS ISSUES	6
5.	PROCESS REACTIONS	10
6.	LOGISTIC FACTORS	14
7.	PROCESS RISK RANKING	19
8.	CONCLUSIONS	28

1. INTRODUCTION

A number of new copper concentrate leach processes are making steady progress towards commercialization. These processes have the potential to provide economically viable metal production at much smaller plant throughput capacities and at significantly lower capital and operating cost than current smelting processes. Some leach processes have already crossed the commercialization threshold and can now be regarded as commercially proven on the basis of at least one large-scale commercial copper leaching plant in successful operation. These include the Western Metals chalcocite low pressure leach process at Mt Gordon, the NSC pressure oxidation leach process at Sunshine Mining and the chloride-sulphate leach process at Pasminco Port Pirie, although the latter process is used to treat matte rather than a copper concentrate or ore.

Other processes such as Intec, CESL, Activox, BacTech/Mintek and Gencor are still at the demonstration plant scale, but hoping to be in commercial production in the near future. Some of the hopefuls may require a final major demonstration plant run, preferably in commercially scalable equipment, to confirm final validity of both process performance and economics for the first major commercial client or joint venture partner. Others may simply be hunting for the elusive combination of the right deposit, mineral composition, mine location, concentrate grade, plant scale, client type and project financier, as might be necessary to best confirm economic viability and fund the first commercial scale operation.

The process developers range from small process orientated companies to large international mining majors. Thus on the one hand the developer might be a smaller scale operating, testing or operating company with an innovative idea such as Intec, Bactech/Mintek, Western Minerals Technologies, Western Metals (formerly Aberfoyle) or Hydrometallurgical Research Laboratories. Such a company may have developed a process for one deposit based on innovative in-house technology and found the same process to be applicable to other deposits.

On the other hand, the process developer might be one of the major international mining companies such as Cominco or BHP, who have developed a new process for their own internal needs. Alternatively it might be a company like Gencor or Dynatec, which seek to primarily use newly developed in-house processes to acquire equity in other projects.

Other combinations of process development and operating companies are also possible. In all cases there needs to be a process champion who has driven the development of the process technology within each company and overcome the myriad technical, financial and corporate obstacles and risks that always arise with each new process and/or project development.

This paper attempts to provide a simplified overview of many of the new copper concentrate leach processes. It addresses key elements such as how different processes handle different oxidation conditions, leach solution chemistry and leach temperatures. It also considers simplified reaction mechanisms, heats of reaction due to sulphide oxidation, and the leaching and disposal of iron, sulphur, copper, precious metals and metal impurities in products and/or by-products. In addition it attempts to rank the relative complexity of different processes and their potential flexibility to respond to varying concentrate mineral compositions.

Logistic issues affecting the optimum location of the plant such as the relative costs of reagents, fuel and power, the concentrate grade versus copper recovery relationship and the costs of concentrate shipment to sites other than the mine site are also considered. Above all, the paper seeks to highlight process issues that need to be considered when trying to select the most appropriate process for a given new mine and/or concentrate composition.

2. SUMMARY

A large number of new concentrate leach processes are currently approaching commercialization status. They all face varying levels of process, engineering and economic risk until the first commercial plant for each process has been successfully put into operation and the process, technical and financial benefits clearly demonstrated.

Existing commercial leach processes would appear to offer potentially lower development risks, because of their known materials of construction and their established track record for copper leach extraction and copper product quality. Uncertainties however still exist in the levels to be expected for copper leach and precious metal recoveries and for capital and operating costs from different feed materials. Significant amounts of time and money will therefore need to be spent by any potential process user in confirming the expected recoveries and costs for each significantly different feed material.

The basis for selection of a completely new process over an existing commercial process is therefore not straightforward. It may depend more on corporate politics and the level of confidence in the claims of the process developer rather than on the actual performance record from an existing similar commercial operation.

No matter which process is ultimately selected, mass and energy balance requirements will set limits on allowable process flowsheet configurations, process design criteria and heating and cooling requirements. Logistic requirements and environmental standards will lead to further constraints.

The most attractive concentrate leach processes would appear to be those that readily lend themselves to low initial capital costs and competitive operating costs, high metal and bullion recovery, minimum environmental impact and rapid response to unexpected variations in plant grade changes and/or throughput capacity. They should also preferably be capable of expansion in modular form. Processes with low initial capital costs should provide an easier task in raising development capital. Lower capital cost plants are therefore more likely to be favored in the initial wave of new concentrate leach developments.

This paper briefly reviews and contrasts the characteristics of many of these new leach processes. The issues of sulphur recovery, reaction heat loads, precious metals recovery and environmental disposal are considered. A checklist of factors for reviewing different processes is provided. A simplified risk evaluation for some of the process options is included.

3. PROCESS OPTIONS

Hydrometallurgical processing options available to new copper concentrate producers include the following smaller to medium-scale on-site or regional process treatment plants rather than the more traditional and often remotely located large-scale custom smelters and refiners:

- Commercially proven processes:
 - Chloride-sulphate copper leaching process – a hot atmospheric agitation chloride-sulphate leach/SX/EW process used by Pasminco at Port Pirie, South Australia for leaching copper matte and recently proposed by Engineering Contractor Ausenco for leaching low grade chalcopyrite ore
 - Western Metals Mt Gordon, Qld., Australia, chalcocite ore leaching process – a hot, low pressure oxygen and atmospheric leach/SX/EW process using ferric sulphate and a moderate grind of 75 microns
 - Sunshine Mining and Refining, Idaho, USA, and The Centre for Advanced Mineral Processing, Butte, Montana, USA. Nitrogen species catalyzed (NSC) sulphate pressure oxidation leach/SX/EW process for leaching argentiferous- tetrahedrite concentrates containing chalcocite copper. Ultrafine grind of 80% passing 10 microns. Moderate temperature (125-155C). Sulphur recovered mainly as elemental sulphur. Conversion to sulphate at higher temperature. Copper recovered as cathode. Chalcopyrite leaching tested successfully in laboratory. Plant closed due to shortage of suitable feed material
- Demonstration scale processes:
 - Intec Sydney, NSW, Australia chalcopyrite or chalcocite concentrate leaching process – a hot (80-85C), atmospheric, copper “Halex” (chloro bromide, BrCl_2) leach/EW process producing copper dendrites, silver salt and gold. Has significant advantages for smaller scale treatment of copper concentrates with high gold credits, possibly high impurity levels and high freight costs to a smelter. Sulphur principally converted to elemental sulphur in the leach residue. Iron precipitation as goethite/akaganeite. Minor sulphur rejection as gypsum. Pyrite attack variable from nil to partial. Reagents air, limestone, NaCl, NaBr, HCl. No SX. Novel membrane EW cells
 - Activox, Western Minerals Technologies, Perth, WA, chalcopyrite or chalcocite concentrate leaching process – an ultra fine grind (5-15 microns), low pressure (150 psi) oxygen leach/SX/EW process at a relatively low leach temperature of 100 -110C, or below melting point of sulphur. LME cathode copper and precious metal production. Sulphur produced as a mixture of elemental sulphur and sulphate. Precious metals recovered by cyanidation of sulphur bearing leach tails. Iron precipitation as haematite, goethite or jarosite. Sulphate bleed and precipitation as gypsum. Reagents oxygen, limestone, lime, H_2SO_4 EW make-up.

- CESL, Cominco, Vancouver, Canada, chalcopyrite and chalcocite concentrate leaching process – light grind (95% passing 45 micron), medium high temperature (150C), two stage chloride-sulphate leach/SX/EW process using high pressure oxygen (200 psi), sulphur extraction and high purity sulphur recovery from leach residue. High-pressure tailings oxidation leach and precious metals recovery from the pressure oxidation leach residue by cyanide. Sulphur recovery as elemental sulphur for possible by-product sale. Soluble iron rejection as hematite. Minor sulphur rejection from bleed stream as gypsum. Minor non-copper soluble metal salts rejection from bleed as hydroxides. Pyrite only partly attacked. Reagents NaCl, H₂SO₄ for leach and EW, limestone, lime, perchlorethylene for sulphur extraction, NaCN for gold recovery
- Nenatech, Brisbane, Australia, chalcopyrite concentrate leaching process, developed by Highland Pacific (Highlands Gold) and MIM – fine grind to 20 microns, ferric sulphate leaching at 80C and atmospheric pressure with oxygen sparging, sulphur largely oxidized to sulphate, limestone precipitation of iron and sulphate, gold recovery by leach residue cyanidation,
- Bactech/Mintek, Perth, WA and Johannesburg, SA, chalcocite concentrate and emerging chalcopyrite concentrate leaching – moderate grind, low temperature, two-stage ferric sulphate atmospheric leach/SX/EW process using air and ferric regeneration with air. Mesophiles at 36-40C for secondary sulphides and moderate to extreme thermophiles at 45-50 and 70C respectively for chalcopyrite. Sulphur recovery as part elemental sulphur in leach residue (indirect process) and part sulphate, which is precipitated from a bleed stream as gypsum. Precious metals recovery by cyanidation of leach residue. Soluble iron precipitated as hydronium jarosite. Pyrite not attacked. Reagents H₂SO₄ for leach and EW, air, limestone, lime, NaCN.
- Billiton BioCOP, Johannesburg, SA, no ultrafine grind, possible ferric preleach, leach/SX/EW. Mesophile bioleaching at 42-45 for secondary sulphide copper leaching and thermophile bioleaching at 70-80C for chalcopyrite leaching. Residue flotation for sulphide copper and precious metals recovery. Precious metals recovery also by cyanidation of leach residue. Reagents similar to BacTech/Mintek.
- Dynatec (formerly Sherritt International Consultants), Fort Saskatchewan, Calgary, Canada, chalcopyrite or chalcocite leaching process – fine grind (90% passing 25 micron), medium pressure, medium temperature (150C chalcopyrite, 100C chalcocite) oxidation leach with carbon addition, residue flotation for copper recycle and sulphur disposal, gold recovery by cyanide leach. Sulphur largely reporting as elemental sulphur. Pyrite oxidized to sulphate. Iron precipitated as haematite. Reagents oxygen, air, finely divided coal, limestone and lime.
- High pressure oxidation process for chalcopyrite concentrates containing gold (e.g. as proposed by Placer Dome, Vancouver, Canada) – no fine grinding, no chloride or other catalyst, no elemental sulphur to recover or to store in tailings. High temperature (200-225C) leach/SX/EW process. Gold recovery from leach residue by cyanidation after neutralization. Reagents oxygen, acid make-up for EW, limestone, lime and NaCN.

Further details and flowsheets for these or related processes can be found in the following references:

Alta 2000 Copper –6 Symposium:

- The Treatment of Copper Ores and Concentrates with Nitrogen Species Catalyzed Pressure Leaching, Corby G Anderson, The Center for Advanced Mineral and Metallurgical Processing, USA

Alta 99 Copper Sulphides Symposium papers:

- Hydrometallurgical Treatment of Copper Sulphides – Are We On the Brink?, A Taylor, M.L.Jansen, International Project Development Services, Australia
- Design of the Mt Gordon Chalcocite Project, K. Baxter, C. Kaiser, Bateman Australia, G.D. Richmond, Western Metals Resources, Australia
- The Commissioning and Operation of a Copper Sulphide Pressure Oxidation Leach Process at Mt Gordon, G.D. Richmond, M.A. Christie, Western Metals Resources, Australia
- CESL Process Update on Demonstration Plant Operations – Copper and Precious Metals Recovery 1998-99, C. Barr, J. Hestrin, Cominco Engineering Services Ltd., Canada
- Chloride-Sulphate Leaching from Chalcopyrite Ores from Sabah, R.T. O'Brien, Leadstar SDN BHD Malaysia, C.A. McDonald, Ausenco, Australia and N.E. Meadows, Straits Resources, Australia
- Bioleaching of Copper Sulphide Concentrates with Mesophiles and Thermophiles, D.Dew, R. Muhlbauer, C. Van Buren, Billiton Research, South Africa
- Private Meeting Notes, Alta Cu 99 Sulphide Hydrometallurgy Roundtable, M.L.Jansen and A Taylor

Alta 98 Copper Sulphides Symposium:

- The Mintek/Bactech Copper Bioleach Process, P.J. Van Staden, Mintek, South Africa
- Bacterial Oxidation of Mt Lyell Copper concentrates, M. Rhodes, Bactech, Australia
- Operation of the Intec Copper "One" TPD Demonstration Plant, J. Moyes, K. Severs, P. Wood, Intec Copper, Australia
- Economic Implication of the Intec Copper Process for the World's Copper Industry, K.Severs, P.Wood, Intec Copper, Australia
- CESL Process for Copper Sulphides: Operation of the Demonstration Plant, D.Jones, J.Hestrin, Cominco Engineering Services Ltd., Canada
- Copper processing in the Dynatec Mini Plant, M. Collins, K. Buban, F. De Kock, R. Kalanchey, T. Xue, Dynatec Corporation, Canada
- The Economics of Autoclaving Chalcopyrite, J. King, Placer Dome, Canada
- Economics of On-Site Treatment of Copper Concentrates, M. Jansen, A. Taylor, IPDS Australia; B. Ellis, Australian Resources Limited, Australia

CIM Paper:

- Process Development Studies by Dynatec for the Pressure Leaching of HBMS Copper Sulphide Concentrates, J. Stiksmas, M. J. Collins, P. Holloway, I. M. Masters (Dynatec) and G. J. Desroches (HBMS), CIM Bulletin, Vol 23, No 104, p 118-123

4. PROCESS ISSUES

4.1 PROCESS FLOWSHEETS

Simplified process flowsheets for the processes described in Section 3 are available in a summary paper presented by A. Taylor and M.L. Jansen at the Alta 99 Cu Symposium in Brisbane.

A more basic overall block model showing generalized process inputs and outputs is shown in Fig 1. Note that the combination of process design criteria, reaction chemistry, thermodynamics and mass and energy balances defines the composition, production rate and temperature of all solid, solution and gaseous products and by-products as well as all process utility requirements.

4.2 MASS AND ENERGY BALANCE REQUIREMENTS

Mass balance and energy balance requirements include:

- Total mass balance: Feed mass input (solids, solution and gases) = Product mass output (solids, solutions and gases)
- Element mass balance: Mass in = mass out for each element
- Heat balance: Heat input + Heat of reaction = Heat output (solid, solution and gaseous products and by-products)

4.3 PROCESS INPUTS

Process inputs include:

- Copper concentrate solids
- Accompanying water in the filter cake or partly dried solids
- Reactants such as:
 - Oxidants including oxygen, air, or indirect oxidants such as Intec's "Halex" to convert selected sulphides to sulphur and/or sulphate
 - Sulphuric acid for EW make-up
 - Sulphuric acid for leach acid make-up to enable all concentrate sulphur to be converted to elemental sulphur
 - Leach solution make-up including sodium chloride or in the case Intec sodium bromide
 - Limestone for neutralization of excess or bleed sulphuric acid
 - Limestone for neutralization and precipitation of soluble sulphates of iron and aluminium
 - Lime for neutralization of sulphate bleed streams and precipitation of metal hydroxides
 - Carbon for sulphur collection in Dynatec process or gold absorption in gold leach processes
 - Recycled copper dendrites for selected base metal precipitation or copper reduction in the Intec process

- SX or IX reagent make-up
- Water for washing of leach residues to remove soluble copper from residue filter cakes
- Water for make-up of evaporation losses
- Electrical energy for mixing, grinding in some case and for EW
- Steam for heating in some cases
- Process water of varying purity for cooling, boiler make-up, EW make-up, wash water, and general evaporation losses
- Various filtration, thickening and solution clarity aids
- Initial plant reagent fill and ongoing steady state process needs

4.4 PROCESS OUTPUTS

Process outputs include:

- Metallic copper (LME cathode, powder or dendrites)
- Solid or solution by-product outputs such as:
 - unoxidised sulphide feed materials in the leach residue particularly sulphides of copper, iron and other base metals
 - sulphide oxidation reaction products and by-products including:
 - elemental sulphur from some processes
 - sulphate sulphur as gypsum
 - sulphate sulphur as jarosite in some cases
 - iron oxidation products such as haematite, goethite or ferric arsenate
 - soluble metal sulphates of certain base, alkali and other metals in a bleed stream for subsequent metal recovery by processes such as:
 - lime precipitation of hydroxides
 - evaporation of sulphates in an evaporator or tailings dam
 - ion exchange
 - soluble or insoluble Se, Cd, Bi, As, Hg in the leach residue
 - precious metals
- Cyanide leach solutions in tailings dam or other containment structures and
- Gaseous reaction products such as:
 - carbon dioxide from neutralization of by-product sulphuric acid with limestone
 - reactor off gases such as steam blow down or air or oxygen saturated with water vapour
 - unexpected releases of bromine or chlorine from the Intec process, perchlorethylene from the CESL process, or hydrogen cyanide from cyanidation of reaction leach residues

- Exothermic heat of reaction due to sulphide sulphur conversion to sulphate and requiring control of reaction temperature by:
 - feed pulp dilution
 - direct or indirect heat exchange
 - oxidant minimization

4.5 ENVIRONMENTAL, HEALTH AND COMMUNITY CONSTRAINTS

Current and future environmental, health and community constraints that should be considered in any process selection process include:

- possible acid mine drainage run-off or leakage due to long term oxidation of sulphide residues or elemental sulphur residues stored in tailings dams or in other surface storage structures
- leach residue storage options such as:
 - filter cake cells near the processing plant
 - filter cake cells at the mine site rather than the process plant site
 - separation of elemental sulphur from sulphide mineral components for possible later sale and/or reprocessing
 - intermixing of leach residue solids with process solutions in an sealed evaporation pond
 - intermixing of leach residue solids with concentrator tails in a tailings dam at the mine site
- worker dust exposure during fine particulate handling
- worker acid mist exposure in EW tankhouse operations
- worker organic vapour exposure from SX settlers and tanks

4.6 OTHER ISSUES

Other areas that need to be addressed in a review of the results achieved by different processes and to select a preferred process include:

- adequacy of sampling, laboratory and pilot plant testwork, process simulation studies and process design criteria, especially for plant feed materials expected during the early years of plant operations
- process complexity
- number of sequential process steps
- ease of process control
- extent of potential scaling by gypsum, goethite or hematite in leach reactors and/or downstream piping and processes
- adequacy of process storage buffers to even out upsets between key unit operations
- relative economic importance of precious metals and copper recoveries during mine life

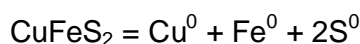
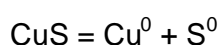
- capacity, availability and cost competitiveness of fuel, power, water, road and/or rail infrastructure at the process plant site
- potential for sale of surplus power to a commercial power grid from a gas turbine or acid plant located at the plant site
- potential for sale of by-product sulphur or by-product acid for on-site treatment of oxide leach ores near the plant site
- risk of not achieving plant design availability due to unforeseen operational problems and/or inadequate process storage
- risk of corrosion due to incorrect materials of construction selection or weld specification
- risk of not achieving design capacity due to plant scale-up difficulties and/or unexpected feed material composition change
- flexibility of process to adjust for variable ore grades and/or mineralogy
- risk of key infrastructure failure or unexpectedly low infrastructure availability
- flexibility to achieve expansion in modest capacity increments
- minimum commercial throughput for each process
- ease/difficulty of capital raising for a particular process
- size of capital requirement for the minimum plant size
- potential for operation as a small-scale custom treatment plant providing a substantially lower cost alternative than a regional or off-shore smelter

5. PROCESS REACTIONS

5.1 CHALCOCITE OXIDATION

5.1.1 Ideal Reactions

Ideally, we would like to see the following simplified overall leaching reactions take place to convert typical concentrate feed minerals of chalcocite, covellite or chalcopyrite to final products of metallic copper and sulphur:



To produce electrowon copper, we require a feed solution to electrowinning of relatively high purity copper sulphate, although for some new processes feed solutions of other copper salts could be considered to be equally acceptable.

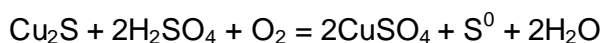
To generate copper sulphate we in turn would need to first oxidize the sulphide ion in the copper mineral to cupric copper (unless already present in cupric form in the feed mineral). We would also need to have available the corresponding amount of sulphate to go with the copper.

This sulphate could either be introduced to the leach as fresh sulphuric acid purchased from an acid plant or it could be introduced as recycled raffinate from the copper solvent extraction process. In either case elemental sulphur could form from sulphide oxidation in the leach process, provided that the appropriate conditions of sulphide oxidation are maintained.

An alternative sulphide reaction product to elemental sulphur, and by far the more usual oxidation reaction product, would be sulphate sulphur. In this case a reduced quantity of fresh or recycled sulphuric acid addition would be added to the leach step.

5.1.2 Sulphide conversion to sulphur

The following equations show the conditions needed for chalcocite conversion to copper sulphate. The need to add oxygen and acid to balance the reaction is clearly evident. In the reaction for elemental sulphur formation from chalcocite we have:

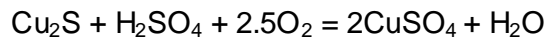


This equation shows that 4 moles of oxygen are required to form 2 moles of CuSO_4 , and that these moles of oxygen are provided by 2 moles of sulphuric acid addition per mole of chalcocite. The reaction also shows that only 1.0 mole of oxygen is needed to form water in association with the hydrogen ions released from the sulphuric acid.

A more complex reaction requiring only one mole of sulphuric acid addition per mole of chalcocite is when basic copper sulphate ($\text{CuO} \cdot \text{CuSO}_4$) is formed from chalcocite oxidation instead of copper sulphate in the primary oxidation step, as in the CESL concentrate leach process.

5.1.3 Sulphide conversion to sulphate

The alternative complete oxidation reactor to convert all chalcocite copper to sulphate copper is as follows:



This reaction shows that the oxygen in CuSO_4 is now partly provided by 1 mole of sulphuric acid addition per mole of chalcocite and partly by 2 moles of oxygen addition per mole of chalcocite.. Another 0.5 moles of oxygen are needed to form water with the hydrogen ions released from the sulphuric acid reaction.

The full oxidation equation for chalcocite suggests that the oxygen requirements to form CuSO_4 from Cu_2S cannot be assumed to involve just 4 moles of oxygen per mole of chalcocite sulphur, as one might intuitively hope for, without also considering the reaction chemistry of chalcocite oxidation. Instead there are either 1 or 2.5 moles of oxygen required and correspondingly 2.0 and 1.0 moles of sulphuric acid also required. Clearly reaction stoichiometry needs to be considered when trying to estimate the oxygen and acid requirements for chalcocite oxidation to CuSO_4 and S.

5.1.4 Emf Control

After having considered the necessary reaction stoichiometry, it is then necessary to determine whether the reaction is thermodynamically favourable and what particular reaction conditions are needed to drive the reaction to either partial or full completion. To maintain the reaction within a desired emf range, it may be necessary to control the emf by holding a certain $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio in the leach solution. Emf control may require two or more stages of countercurrent leaching with different emf ratios in each leach stage. Alternatively it may require a large excess of total iron to hold the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio effectively constant, even though part of the Fe^{3+} is reduced to Fe^{2+} .

Thus, from a consideration of reaction stoichiometry, emf requirements and practical process flowsheet constraints, it can be seen that control of the reaction emf might lead to varying combinations of process steps. These could include multistage leaching, recycle of solutions with high ferric reactant concentrations, recycle of high concentrations of sulphuric acid (possibly at an even a higher acid concentration than those readily available in the SX raffinate) and control of water balance in the leach, wash and bleed circuits.

5.1.5 Soluble Salts

To prevent soluble salts from increasing to unacceptable concentration levels where materials of construction or product quality might be at risk, bleed streams may be needed for soluble salt concentration control. In addition precipitation and neutralization reagents such as limestone or lime are likely to be used to form gypsum to reduce sulphate and soluble metal concentrations in bleed streams and to do this in a manner which limits unacceptable scaling of pipes and/or equipment.

5.1.6 Sulphur Encapsulation of Precious Metals

Care also needs to be taken to avoid possible encapsulation of the leach residue with any reaction by-product. Depending on the process, such encapsulation might limit later limit the later ability to directly cyanide leach the residue for precious metals recovery or to float off and separately recover by-product elemental sulphur for sale and an unleached sulphide copper concentrate for separate precious metals recovery.

5.1.7 Heat of Reaction

Heat liberation due to sulphide oxidation during leaching will probably require indirect external cooling for temperature control. The extent of cooling will depend on the sulphur content of the feed, the percent conversion of sulphide to sulphate, the percent solids in leaching, the manner of oxygen addition or aeration and the loss of water vapour in the reactor off-gases. Some indication of heat evolution and cooling requirements can be gained by consideration of the following examples of chalcocite and chalcopyrite leaching:

Sulphide Heat of Reaction - Full Conversion to Sulphate:



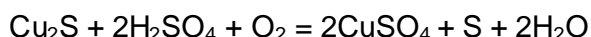
Net heat of reaction: Net heat of reaction at 25C is given in Perry, Chemical Engineers Handbook, by $-68.31 + 2(-200.8) - (2.5(0) + (-212.0) + (-18.97)) = -238.9$ kcal per gmole chalcocite. This is equivalent to -7.48 kcal per g sulphur.

Sulphur content: If the feed material were a high-grade ore or low-grade concentrate containing say 12% sulphur in a 10% solids slurry, we would have a heat of reaction per g of solid feed material of -0.898 kcal. This is equivalent to approx. 95°C temperature rise, based on a solution specific heat of 1.0 cal/g. $^\circ\text{C}$ and a solids specific heat of 0.2 cal/g. $^\circ\text{C}$.

Thus, we might cope with minimal cooling requirements when leaching a dilute slurry of chalcocite ore containing say 12% S. However, we would need substantial cooling services if trying to maintain the maximum possible leaching rate of a chalcocite concentrate containing say 20% S. Much greater cooling capacity still would be needed when treating a pure chalcopyrite concentrate containing 35% S, or an impure chalcopyrite concentrate containing say 40%S.

Complete oxidation of all sulphides might be preferred if gold is to be subsequently leached from the leach residue. This might also encourage us to select a high-pressure oxidation process to ensure full ferrous/ferric sulphate conversion to hematite or goethite. However, we would have less cooling requirements and possibly a greatly simplified sulphur residue disposal problem if we could control the extent of sulphur oxidation to ensure that only elemental sulphur is formed. There therefore remains a strong incentive to consider leach processes that use less oxygen to oxidize sulphur but still provide high recoveries from precious metals leaching.

Heat of Reaction – Sulphide Conversion to Elemental Sulphur:



Net heat of reaction at 25C is given in Perry, Chemical Engineers Handbook, as $-68.31 + 2(-200.8) + 0 - (0 + 2(-212.0) + (-18.97)) = -26.9$ kcal per gmole chalcocite, or about 11% of the heat of reaction for sulphate formation. This is equivalent to -0.84 kcal per g sulphur in chalcocite. If the feed material were a high-grade ore or low-grade concentrate containing 12% sulphur in a 10% solids slurry, we would have a heat of reaction per g of solid feed material of -0.17 kcal. This is equivalent to approx. 18°C temperature rise, based on a solution specific heat of 1.0 cal/g. $^\circ\text{C}$ and a solids specific heat of 0.2 cal/g. $^\circ\text{C}$. Thus, there would be almost no cooling required when leaching a dilute slurry of chalcocite ore containing say 12% S, provided that the reaction conditions were controlled to limit the conversion to elemental sulphur. Minimal though slightly more cooling would be needed if converting a chalcocite concentrate containing say 20% S to elemental sulphur. However, almost triple the cooling capacity would be required if converting a pure chalcopyrite concentrate containing 35% S or an impure chalcopyrite concentrate containing say 40%S to elemental sulphur. Any uncontrolled side reactions with pyrite or pyrrhotite, leading to additional conversion of sulphide to sulphate, would add to the oxygen demand and the cooling load.

Heat of Reaction – Ferrous Sulphate Conversion to Ferric Sulphate

One recent literature source suggested that significant heat evolution occurs during the conversion of ferrous sulphate to ferric sulphate. This seems surprising since no sulphide oxidation is involved in the reaction. By evaluation of the stoichiometry of the reaction, we see that the reaction is given by:



Net heat of reaction is therefore $-68.32 + (-653.3) - (-212.0 + 0.5(0) + 2(-236.2)) = -37.2$ kcal/g mole ferric sulphate = -18.6 kcal/g mole SO_4 in ferrous sulphate = -0.6 kcal/g sulphur in ferrous sulphate.

Thus, net heat of reaction for conversion of 1g of sulphur in ferrous sulphate to ferric sulphate is approximately:

- the same as the heat of reaction for conversion of 1 g of sulphide sulphur to elemental sulphur (-0.84 kcal/g sulphur in sulphide)
- 11% of the heat of reaction for conversion of 1 g of sulphide sulphur to sulphate sulphur (-7.48 kcal/g sulphur in sulphide)

The claim that ferrous sulphate oxidation to ferric sulphate is a significant contributor to the heat of reaction therefore appears to be overstated. Ferrous oxidation appears to be a relatively mildly exothermic reaction of similar order of magnitude to the heat of reaction for conversion of sulphide sulphur to elemental sulphur by oxygen.

5.1.8 Precious Metals Recovery:

Precious metals recovery is highly significant for concentrates carrying a high precious metals value. The selection of a preferred leaching process will therefore be highly dependent on the level of precious metals extraction achieved by that process.

The Activox, Albion (Nenatch) and Intec processes claim to be able to recover very high (+95%) levels of precious metals from elemental sulphur bearing leach residues without the need for full sulphur oxidation during the leach.

On the other hand the BacTech/Mintek process appears to yield only intermediate levels of precious metal recovery. Further process improvements are understood to be continuing.

The difference in precious metals recoveries between different processes is presumably related to a range of factors. These factors are expected to include the nature of the elemental sulphur formed during leaching, the extent of coating of leach residue minerals by elemental sulphur and the extent to which precious metal grains may be free or locked inside residual sulphides, goethite, haematite, jarosite or other leach residue minerals.

The Dynatec and CESL leach processes both recover precious metals from the sulphide leach residue by firstly removing elemental sulphur and then either leaching the resulting residue as is (Dynatec) or after further sulphur/sulphide removal pretreatment (CESL). The Dynatec process recovers sulphur from the leach residue by absorption in coal, which is added as part of the sulphate leach feed. The coal is recovered by flotation at the end of the leach. The CESL process recovers elemental sulphur by flotation and solvent extraction of solid sulphur from the leach residue. Pressure oxidation is used to oxidize the remaining sulphide sulphur in the leach residue and cyanidation of the fully oxidized pressure leach residue is used to recover precious metals.

In a later version of the Dynatec process, the precious metals are recovered from the sulphide leach flotation tails instead of from the sulphur depleted sulphide leach residue.

6. LOGISTIC FACTORS

6.1 SOLID REACTION PRODUCTS

Concentrate leach circuits usually include one or more of the following solids handling operations:

- Feed concentrate grinding which might be minor or major depending on the process and the desired reaction rate
- Filtration of the feed concentrate after grinding to minimize unwanted input of fresh water into the leach circuit and added costs for bleed solution treatment
- Countercurrent leaching with intermediate thickening and/or filtration of leach solids to maximize leach reactant driving force and overall metal recovery, where necessary
- Clarification of solutions to minimize crud formation in solvent extraction (SX) from entrained or precipitated solids in the pregnant leach liquor, and solids impurity transfer to electrowinning (EW) or other forms of final metal recovery
- Sand/slimes separation if required for improved leach solids handling and washing
- Gypsum precipitation and filtration or thickening before discharge to a tailings impoundment, to remove soluble sulphate from circuit bleed solutions
- Flotation of residual sulphides in the leach residue for recovery of residual sulphides, copper and precious metal for either recycle to leach (with or without subsequent regrind), sale as an upgraded leach concentrate or treatment by cyanide or other gold extractant for bullion recovery
- Flotation of by-product elemental sulphur for either disposal as crude sulphur or later upgrading to high purity sulphur
- Filtration of flotation products to limit moisture transport costs
- Gypsum removal from piping and/or SX thickeners if gypsum solubility exceeds saturation levels in the leach circuit
- Solids removal from floor and weirs of SX settlers due to unexpected precipitation under changed pH conditions, silica or other metal solubility limits being exceeded or crud formation
- Anode slime removal from electrowinning cells
- Copper cathode, dendrites or powder removal, washing, filtration, drying and transport
- Precious metals production as a bullion or possibly even as high purity electrowon cathode from EMEW or other electrowinning cell.

Depending on the percent conversion of sulphide sulphur in the feed concentrates to elemental sulphur and/or sulphate and the type of feed minerals present in the concentrate, the weight of reaction products might vary from say 120% to 200% of the concentrate feed weight. The disposal of these by-products may therefore be a significant challenge to each new process. If it is not possible to send the leach residue to a conveniently located tailings dam, it may be necessary to filter the residue and ship a filter cake to a local landfill site or back to the mine site.

The cost of product disposal might therefore become a significant process cost item for certain plant locations. An indication of the cost of transport in Australia can be gained by assuming a product road or rail transport cost of A10c/t km (US6c/t km) and/or a distance insensitive sea transport cost of say A\$100/ tonne, excluding 10% GST.

6.2 LIQUID REACTION PRODUCTS

Soluble reaction products left over after neutralization to pH 10.0 of tailings and/or bleed streams can include soluble sulphates, chlorides and silicates of alkali metals and sometimes also of low level base metal impurities. If enclosed in an evaporation pond of adequate area, these soluble salts will start crystallizing. If the size and/or cost of an evaporation pond is excessive, it may be necessary to adopt membrane concentration and/or brine concentration (e.g. RCCI brine concentrator) as used for treatment of fly ash and various blow down streams from power stations in the USA and Australia.

Alternatively, it may be possible at some stage in the not too distant future to recover acid from bleed streams by membrane separation and recycle it back to leach in more concentrated form before neutralization of the remaining barren solution.

Another option is to use alkaline flotation tailings to neutralize acidic sulphate solutions. The tailings would need to be produced from a flotation plant situated on the same site as the concentrate treatment plant. Care would however need to be taken to ensure that harmful soluble elements were not introduced to the flotation circuit though water recirculation from the tailings neutralization circuit.

Organic entrainment in raffinate reporting to bleed streams from SX plants should preferably be minimal, if appropriate organic recovery devices are in place.

6.3 PLANT RAW MATERIALS AND CONSUMABLES

Just as residue and reaction by-product weights can frequently be 1.5-2.0 times the concentrate feed weight, combined raw material inputs to a concentrate processing plant such as sulphuric acid, limestone and lime can also easily exceed the concentrate feed weight. In fact the only weight losses are usually relatively minor carbon dioxide losses associated with excess acid and/or soluble sulphate precipitation by limestone.

Power can be expensive at a remote site if based on on-site power generation using imported distillate or fuel oil, which has had to travel a long distance from the nearest coastal port. On the other hand power cost might be quite low, if taken from a nearby low cost power grid or if generated from natural gas supplied from a nearby regional mains gas line. In the case of a plant being located at significant distances from either power or gas supply, it is usually more cost effective to transport gas say up to 150 km from a gas mains for energy generation. The possibility of sale of surplus power from any on-site acid plant into the regional power grid also needs to be considered, if in fact there is a regional power grid. Some states of Australia provide easier access to the grid and provide much better buy back terms than others.

The combined sum of operating costs for raw materials transport, product transport, labour, energy usage, tailings disposal and the value of base metals left behind in leach tailings needs to be a minimum if plant operating costs are to be optimized. Comparison of operating costs for different leaching sites and different concentrate grades should enable the optimum plant location to be determined for the case of a high-recovery bulk concentrate versus a lower recovery smelter concentrate. The preferred treatment location might be say a smelter for high concentrate grades in the early years of operation when mine and concentrator performance is still being established and a coastal port for the same concentrate when concentrate production becomes more certain and more routine. It is worth noting that the optimum concentrate treatment site location may not necessarily be the same as the mine site location.

The availability of by-product acid of a suitable concentration for use in heap leaching of oxide ores near the mine site might also be an important factor in determining the optimum plant site. A remote coastal location might be less attractive, because by-product acid concentration might be so low as to be uneconomic to use for leaching of other products at that location. On the other hand if high-grade sulphur were produced as a by-product, it could be shipped back inland for on-site commercial grade acid manufacture from an acid plant and associated by-product power production. A slightly lower grade of sulphur might also be shipped back to the mine site at relatively similar transport costs but possibly for bacterial production of acid for on-site heap leaching.

The time taken to obtain environmental permits at different locations can also be an important factor in the choice of process. Permitting conditions are possibly much more stringent near a major coastal town than at a remote mine site and for a concentrate treatment plant rather than a concentrator.

The size of the treatment plant and the possible requirement to source feedstock from several mines rather than just one mine, in order to achieve and maintain acceptable economies of scale, will also have a major influence on plant location. Costs will usually be minimized by a combination of one or more of the following factors such as the availability of:

- an economically accessible coastal location for the treatment plant
- an associated port with established deep water loading/unloading facilities
- low energy costs from coal or gas fired power generation
- an established electricity grid
- natural gas for heating or on-site co-generation
- an assured supply of adequate quality water
- adequate supplies of acceptable quality limestone for neutralization of acidic and/or sulphate bleed liquors
- suitable land for a plant site
- an acceptable plan and containment materials for non-polluting solid and liquid waste disposal
- a suitably skilled workforce from nearby towns or from a larger regional town connected by fly-in fly-out services if the work force has to travel long distances
- established domestic or international market agreements for production and sale of the main copper product as well as for sale of any important major by-products such as precious metals, sulphur and/or sulphuric acid

- appropriate corporate environmental standards to assist in obtaining early community acceptance of project plans and to minimize permitting and project and mine approval time requirements.
- a politically stable national, state and local government

6.4 INFRASTRUCTURE COSTS

Infrastructure costs depend on the scale of the project, the current state of development of the proposed plant site location and the level of demand for labour, water, fuel, power, process consumables, transport and plant maintenance support services for the proposed project over and above any existing regional services. In many cases there may not be any existing services. However, for any given process, it is not difficult to calculate indicative capital and operating costs for different process options and to thereby rank different sites and different process alternatives on the basis of differing infrastructure costs.

6.5 PROCESS COMPLEXITY AND ENVIRONMENTAL DISPOSAL

Simple processes have a minimum number of unit operations and simple external inputs such as say only sulphuric acid, power, water and limestone. They result in minimum environmental impact and would appear to be provide a preferred processing choice, wherever available for selection.

A good example of a highly successful simple process would be the now well recognized process of copper heap leach/SX/EW. This recognition did not exist in the mid 60's when the process was first introduced for oxide copper ores. At that time the process was considered a novelty by many companies and only suited to limited types of oxide and/or waste sulphide resources. There was only one commercial plant operating, the 5,000 tpa cathode Ranchers Bluebird SX/EW plant in Miami, Arizona. Now, some 35 years later there are scores of small and large leach/SX/EW plants operating around the world successfully treating oxide and sulphide heap leachable ores and yielding some of the lowest cost cathode copper currently produced.

Limits to the acceptability of different sulphide leach processes are likely to arise from both their levels of complexity to operate and the potential environmental impact of their residues. There are understandably concerns about potential environmental impacts from sulphide leach processes including possible future long term acid mine drainage problems from sulphide or sulphur bearing concentrate leach residues. This concern could readily drive the selection of any given process towards a treatment processes that might be more complex or expensive to operate but which might produce more stable solid and/or liquid waste by-products. The solid waste products that might be preferred could be oxide and/or insoluble sulphate leach residues, which have no future environmental liabilities, as opposed to sulphide residues which remain leachable in the presence of oxygen to form acid mine drainage.

Alternatively, it might be argued that finely ground sulphide leach residues could be considered to be perfectly acceptable and stable for long-term disposal, provided that they could be disposed of in a manner similar to that used for formation of in-situ sulphide geological resources. This type of disposal would presumably require some type of tailings burial that is similar to or closely mimics natural geological processes on land and under the sea. Land burial might include clay capping of material below the natural ground topography, preferably below the water table if readily accessible, and with the potential to recover and retreat the material if economics of processing should later become much more favourable.

6.6 KEY POINTS

Logistic factors can have a key influence on the selection of the preferred location for a new sulphide concentrate treatment plant in any particular region. Key factors include not only relative processing input costs but also long-term tailings disposal costs. A simplistic solution requiring complete oxidation of all sulphides to oxides might yield the lowest tailings disposal cost but lead to higher process plant capital and operating costs than desired. Newer processes that involve more complex chemistry but lower operating temperatures, pressures, capital and operating costs might finish up being preferred, because they provide more competitive production costs and therefore more sustainable profit margins under long term decreasing metal prices.

7. PROCESS RISK RANKING

7.1 RISK FACTORS

Risk factors to consider in the development and/or application of a new concentrate treatment process include risks in mining, concentrating, concentrate treatment, political stability, environmental controls and financing. Some of the more important process related risks include:

1. Mining:

- Adequacy of overall resource tonnes and grade
- Extent of associated heap leachable oxide and/or low grade sulphide copper resources (waste or separate resource)
- Extent of local limestone availability for on-site acid neutralization

2. Concentrating:

- Potential variability in resource and plant feed in:
 - mineralogy of base metal sulphides, gangue and precious metals
 - ore hardness and abrasiveness
 - grain size and extent of interlocking of valuable and gangue minerals
- Rougher and cleaner concentrate recovery versus grade relationships
- Type of tailings disposal method and potential for unintended later environmental consequences from either dust or acid mine drainage

3. Concentrate Treatment:

- Magnitude and potential variability in plant feed in:
 - moisture content
 - composition and mineralogy of base metal sulphides, gangue and precious metals
 - chloride or other soluble salt content
 - grain size and extent of interlocking of valuable and gangue minerals
 - sulphide sulphur distribution across different minerals
 - reactive sulphur percentage (base metal sulphides) versus non-reactive sulphur percentage (pyrite generally)
 - smelter penalty elements such as arsenic, selenium, mercury, bismuth, cadmium
 - copper mineral mix especially wt.% chalcopyrite, chalcocite, covellite
 - other base metals mix including covellite and galena
 - iron mineral mix including pyrite and pyrrhotite

- Availability of adequate tonnage and grade of low cost limestone or acid consuming heap leach materials
- The attainment at commercial scale of predicted feasibility study values for:
 - Capital cost
 - Operating cost
 - Start up time
 - Time to achieve design capacity and product grade
 - Copper recovery and grade
 - Precious metals recovery and grade
 - Sulphur recovery and grade (including elemental sulphur and sulphide sulphur)
 - Speed of response to varying concentrate feed grade and mineralogy
 - Leach time
 - Plant availability
 - Maintenance costs
 - Plant safety performance
 - Power consumption
 - Fuel consumption
 - Reagent consumption
 - Impurity metal disposal in a stable solid residue
- Level of complexity involved in construction, operation and maintenance in countries with less advanced technical, operations and maintenance skills

4. Project Financing:

- Number of prior successful process installations
- Scale of pilot or demonstration project
- Country political and economic stability
- Risk of any adverse environmental and/or operational consequences due to inadequate operator and/or technical skills
- Ability to be in lowest quartile of producer costs
- Adequacy of rate of return and profit margin
- Flexibility to produce and sell an off-specification product if unexpected product quality problems should arise
- Risk of insolvency, sale or closure of technology supplier during testing, design and operation of first commercial plant
- Adequacy of engineering of commercial plant

- Adequacy of the demonstration of process for commercial design
- Adequacy of the specification and/or controls on materials of construction during vessel and piping fabrication
- Sensitivity of production costs to energy costs
- Ease of commencement of operations at an initial small scale and relatively low capital cost and later expansion as required

7.2 RISK RANKING

Without attempting an exhaustive analysis, some of the key features of different processes that need to be taken into account when ranking process risks are as follows:

- **High Pressure Oxidation Leach Process:**
 - High temperature (220C), high pressure oxygen leach
 - Leach temperature above sulphur melting point
 - LME grade cathode copper
 - High copper recoveries – Cu >99%
 - High precious metal recoveries – Au >98%
 - Precious metal leaching in separate cyanide leach of alkaline copper leach residue
 - Relatively high capex – say US\$1900/tpa Cu
 - Moderate opex – say US25c/lb Cu at US 2c/kWh
 - Likely to require a large scale operation to be economic
 - Relatively simple process chemistry
 - Requires oxygen plant
 - Requires ample power, preferably low cost
 - Requires ample limestone for neutralization of sulphate, preferably low cost
 - CCD wash circuit for soluble copper recovery
 - Conventional SX/EW
 - All sulphide sulphur converted to sulphate sulphur (approx. 100% conversion)
 - Sulphur rejection as gypsum by bleed solution treatment
 - Pyrite completely oxidized
 - Iron converted to haematite
 - Raffinate bleed required for sulphate and soluble base metal control
 - Leach residue solids mainly iron oxide, minimal unleached sulphides, gypsum and associated base metal and smelter impurities
 - Cyanidation of alkaline leach residue for precious metals recovery

- Reagents oxygen, limestone, lime, NaCN, carbon
- Demonstration of total process in Placer pilot plant
- No commercial plant operation but separate unit operations already operating at commercial scale
- No fine grinding
- No chloride in leach solution
- No long term environmental risks
- **Intec Process:**
 - Atmospheric temperature (85C), atmospheric pressure, aerated leach
 - Leach temperature below sulphur melting point
 - LME Grade A copper production as dendrites
 - High copper recoveries - Cu>98%
 - High precious metal recoveries – Au>95%, Ag>98%
 - Precious metals (Ag, Au) leaching in same leach solution as copper
 - Economic treatment of low (12% Cu) to high grade (+30% Cu) chalcopyrite concentrates
 - Capable of treatment of concentrates with high levels of smelter impurities
 - Low capex – of order of 50% lower than smelting – say US\$1400/tpa Cu
 - Low opex – of order of 35% lower than smelting – say US12c/lb Cu at US6c/kWh and including precious metals recovery
 - Likely to be economic at a small to medium scale
 - Relatively complex process chemistry
 - Novel membrane EW step for cuprous copper
 - Reduced power for EW due to electrowinning of cuprous copper in chloride media versus cupric copper in sulphate media
 - Chloro bromide (“Halex”) leaching agent
 - Sulphide copper sulphur converted mainly to elemental sulphur (approx. 85% conversion)
 - Minor sulphur rejection as gypsum
 - Pyrite generally unreactive
 - Iron converted to goethite/akaganeite
 - Leach residue filter cake mainly iron oxide, elemental sulphur, unleached sulphides, gypsum and associated base metal and smelter impurities
 - Reagents air, limestone, NaCl, NaBr, HCl, carbon

- Power requirement approx. 70% of high pressure acid leach plant SX/EW plant
- Demonstration plant at 1 TPD Cu production rate
- No autoclaves required
- No oxygen plant required
- No fine grinding
- No SX
- No separate solution bleeds
- No separate cyanide or thiosulphate leaching of residue for PM recovery
- Long term environmental issue of sulphur and sulphide reactivity in tailings

NSC Process:

- Intermediate temperature (125-175C), intermediate pressure (630 kPag) oxygen leach
- LME grade cathode copper
- Potential for +99.9% grade Ag production
- Leach temperature above sulphur melting point
- High copper recoveries – Cu >99%
- Fast leach kinetics - <30 minutes leach
- High precious metal recoveries – Au>98%, Ag>96%
- Silver leaching in same leach solution as copper
- Silver recovery from leach solution as insoluble silver chloride by NaCl addition
- Gold leaching by separate thiosulphate leach of alkaline copper leach residue
- Suitable for smelter penalty elements
- Medium capex – say US\$1400/tpa Cu
- Moderate opex – say US\$25c/lb Cu at unspecified power cost
- Likely to be economic at medium scale of operations
- Novel process chemistry
- Requires oxygen plant
- Requires ample power, preferably low cost, for EW of cupric copper
- Requires limestone for neutralization of by-product sulphate
- CCD wash circuit for soluble copper recovery
- Conventional SX/EW

- Chalcopyrite sulphide sulphur converted mainly to elemental sulphur (approx. 85% conversion) at 125C but can be largely converted to sulphate at higher temperature (175C)
- Sulphate rejection as gypsum by bleed solution treatment
- Pyrite oxidized
- Iron converted to ferric sulphate except at lower free acid (10 gpl) and higher leach temperature (175C) where iron precipitation as ferric arsenate and/or possibly haematite occurs
- Raffinate bleed for sulphate and soluble base metal control
- Leach residue solids mainly iron oxide, elemental sulphur (125C leach temperature), minimal unleached sulphides, some gypsum and associated base metal and smelter impurities
- Capability of by-product sodium sulphide and thiosulphate generation by reaction of product elemental sulphur with caustic soda.
- By-product sulphide and thiosulphate potentially usable for gold leaching and/or conversion of regional oxide copper ores to sulphide ores
- Reagents oxygen, limestone, lime, NaNO_2 , NaOH , carbon
- Full scale argentiferous tetrahedrite concentrate leach plant operational at Sunshine Mining from 1985-1995
- Fine grinding – p80 of 10 microns
- Nitrogen species catalyzed leach
- No chloride in leach solution, other than for silver precipitation from pregnant solution
- No leach residue flotation
- No titanium or acid brick lining required in autoclave due to apparent absence of chloride – use SS reactor lining
- No demonstration scale testing of chalcopyrite leach (lab scale only)
- Environmental issues of elemental sulphur and sulphide stability as for other processes
- **CESL Process:**
 - Medium temperature (150C), high pressure (1500 kPa) main oxygen leach
 - Small high temperature (220C), high pressure secondary oxygen leach for leach residue float sulphide concentrate
 - Leach temperature above sulphur melting point
 - Chloride in leach solution
 - LME grade cathode copper
 - High copper recoveries – $\text{Cu} > 99\%$
 - High precious metal recoveries – $\text{Au} > 95\%$, Ag recovery unknown

- Precious metal leaching in separate cyanide leach of alkaline copper leach residue
- High capex – say US\$1900/tpa Cu
- Moderate opex – say US25c/lb Cu at US 2c/kWh
- Likely to be economic at medium scale of operations
- More complex process chemistry
- Requires oxygen plant
- Requires ample power, preferably low cost
- Requires limestone for neutralization of sulphate, preferably low cost
- Filtration/ wash circuits for soluble copper recovery
- Conventional SX/EW, through two interlinked SX circuits
- Sulphide sulphur mainly converted to elemental sulphur (approx. 85% conversion)
- Sulphur rejection as gypsum by bleed solution treatment
- Pyrite not oxidized
- Iron converted to haematite
- Raffinate bleed required for sulphate and soluble base metal control
- Leach residue solids mainly iron oxide, gypsum and associated base metal and smelter impurities
- Elemental sulphur recovered by flotation from secondary leach residue and perchlorethylene treatment to produce saleable by-product sulphur
- Base metal sulphides recovered from secondary leach residue re-leached in high pressure oxidation leach
- Cyanidation of alkaline leach residue for precious metals recovery
- Reagents oxygen, limestone, lime, NaCN, carbon
- Demonstration of total process achieved in CESL demonstration plant
- Titanium autoclave vessels to accommodate high chloride environment
- No commercial plant operation but unit operations largely already operating at commercial scale
- No fine grinding
- No residual sulphides
- Possible low environmental risk associated with elemental sulphur handling

Other processes such as the Bactech/Mintek, Dynatec, Activox and Western Metals process can be evaluated similarly to those considered above.

Various rating factors can readily be used to develop an overall process ranking and to compare different processes on a preliminary basis, if required.

Factors that could be taken into account in the ranking could include the following factors as an example: number of prior commercial operations, scale of demonstration plant, number of unit operations, level of process complexity, capital cost/unit annual metal capacity, minimum initial scale of operations, minimum plant capital cost, likely operating cost, potential copper recovery, potential precious metals recovery and level of process novelty. Other factors might also be considered as necessary. Different weightings could be given to different factors if necessary. The overall rankings derived in this manner, although subjective, could nevertheless help to highlight those factors that are more important than others and to narrow the range of process options that might best be suited for treatment of a given concentrate type at various locations.

The following table is an example of one attempt to rank the level of risk in a selected number of processes (Numbered 1-6) on a greatly simplified basis. The possible value of ten development risk parameters was considered. The values were weighted equally and summed. Other parameters could also have been included if required and different ratings applied, depending on personal preferences for perceived risks.

Out of a possible score of 100 using these particular weighting factors, the commercially applied leach processes (67-68) appeared to be preferred to emerging processes (52-59). However, this ranking could change markedly if different factors are assigned different importance. In particular, it would seem that processes with low initial capital thresholds and high metal recoveries might expect to receive more initial attention than those with high capital thresholds, simply because of the greater ease of raising smaller amounts of capital, especially by mining juniors.

EXAMPLE RANKING OF ALTERNATIVE CONCENTRATE LEACHING PROCESSES

Rating factor	Max Value	Min Value	1	2	3	4	5	6
Number of prior commercial ops	10	0	0	0	0	0	10	10
Scale of pilot or demo plant	10	0	6	8	4	3	4	3
Number of unit operations	0	10	6	3	7	7	7	7
Level of process complexity	0	10	3	3	5	6	7	5
Capital cost/unit capacity	0	10	9	5	6	6	5	7
Operating cost/unit capacity	0	10	9	8	6	6	5	7
Copper recovery %	10	0	8	9	7	6	9	8
Precious metals recovery %	10	0	7	9	5	5	5	5
Minimum scale commercial plant	0	10	9	4	7	7	6	8
Process novelty	0	10	2	4	5	6	10	7
Total out of 100			59	53	52	52	68	67
Example overall ranking			3	4	5	6	1	2

7.3 THE FUTURE

New processes will continue to be developed as mining companies and inventors continually search for lower cost routes to metal production. Even as recently as the last few weeks of August, a new process called the Osleach process has been reported for catalytic leaching of chalcopyrite and enargite concentrates at atmospheric temperature. High copper and precious metals recoveries are claimed and gold producers with difficult gold ores are reportedly interested to evaluate the process. A trial tank leach has been running in Tasmania on chalcopyrite and a full scale demonstration plant is being set up at the Great Australian Copper Mine near Cloncurry, Qld, funded in part by Australian Federal Government Research Grants.

Another new process is the SLS process proposed by SLS Technology in Perth.

There nevertheless remains a costly barrier between coming up with a novel idea and proving a new process through rigorous laboratory, pilot plant and demonstration plant scale testwork through to final commercial scale operations. Costs and times for development of a new process from laboratory scale through to demonstration scale might be typically of the order of \$10-20 million and say 3-10 years for any given process. From detail design through to first commercial plant operation the cost and time might be of the order of a further \$50-\$200 million plus another 3-5 years. There are obviously exceptions to these guidelines, but the costs and times involved are always substantial.

It is expected that possibly only some of the new processes will overcome the final hurdle to commercialization in the next ten years and possibly more by good salesmanship rather than by merits of the process only. For the continued development of commercially viable leaching processes and the ultimate survival of a more profitable base metals industry, it is incumbent on process consultants, engineering companies and mine owners to ensure that adequate due diligence is performed before any process becomes commercial.

Development might be done on a fast track basis such as for the Cawse Nickel project in the recent laterite leaching development race in Western Australia. However, the necessary process engineering, supporting testwork and rigorous detail design must still be carried out to ensure the commercial success of the project. Omitting adequate testwork and engineering is a recipe for disaster, as recent history will tell - whether it is the engineer trying to save costs on a lump sum contract on a poorly defined project scope or the mine owner having insufficient funds to cope with escalating project costs on an inadequate mine and process plant development.

In all cases it is much cheaper to carry out all the necessary testwork and engineering development work at the process development stage rather than to try and resolve unexpected process design and operational problems after the commencement of operations.

8. CONCLUSIONS

1. Hydrometallurgical process options currently available for the treatment of copper concentrates include:
 - a limited number of commercially proven processes such as:
 - the atmospheric chloride-sulphate leach as at Port Pirie
 - Western Metals Mt Gordon low pressure oxygen ferric sulphate leach
 - Nitrogen species catalyzed sulphate pressure oxidation leach
 - a wider range of advanced demonstration scale processes such as:
 - Intec atmospheric Halex leach
 - Activox fine grind low pressure oxygen leach
 - CESL intermediate temperature, two stage, high pressure oxygen chloride leach
 - Nenatech low temperature oxygen-sparged ferric sulphate leach
 - BacTech/Mintek low temperature two stage ferric sulphate bioleach
 - Billiton BioCOP ferric sulphate mesophile and thermophile bioleach
 - Dynatec fine grind medium pressure ferric sulphate leach
 - High pressure oxygen leach
2. Process conditions include varying grind conditions from 10 to 45 microns, leach temperatures of 100 to 250C, varying sulphur oxidation conditions, the use of chloride in the leaching reagent in many cases, nitrogen catalyst in another case and mainly SX/EW for copper production
3. Process products include varying sulphur products of both elemental sulphur and sulphate, copper production mainly as cathode and precious metals as bullion.
4. Process performance requirements include high leach extractions of copper (mid to high 90s) and precious metals (mid to high 90s), in order to be competitive with smelting
5. Logistic factors largely determine where a concentrate treatment plant is best located and whether a bulk concentrate is preferable to more traditional high grade cleaner concentrates
6. Process risk should be minimized wherever possible by the selection of a process which is commercially proven, has low capital and operating costs and yields a stable long term residue
7. Significant differences exist between the different processes for treatment of chalcopyrite with some of these differences as shown below:
 - POX – no grind, all sulphide conversion to sulphate, leach temperature (220C) above sulphur melting point, conventional high pressure oxygen leach technology, standard CCD/SX/EW technology, oxygen plant, precious metals recovery by cyanidation of pressure leach residue, minimum environmental risk from fully oxidized sulphate leach residue

- Bacterial oxidation – variable grind depending on type of bacteria used, part sulphide conversion to elemental sulphur, most sulphide conversion to sulphate, atmospheric leach to 75C, leach temperature below sulphur melting point, air oxidation coupled with bacterial ferric regeneration, sulphate bleed, possible chloride presence, standard SX/EW, no oxygen plant, precious metals recovery by cyanidation, possible environmental risk from elemental sulphur and sulphide sulphur in leach tails
 - CESL – medium to fine grind, sulphide conversion mainly to elemental sulphur, leach temperature above sulphur melting point, chloride required in leach solution, two stage medium temperature oxygen leach (150C then 95C), final high pressure oxygen leach of secondary leach residue concentrate, SX/EW including multiple SX plants, leach residue flotation, high purity sulphur extraction, high pressure high temperature oxidation leach of flotation concentrate, precious metals recovery by cyanidation, oxygen plant, elemental sulphur recovery for sale, possible environmental risk from oxidation of unsold sulphur, titanium pressure vessels, reduced oxygen consumption versus POX oxygen consumption.
 - Intec – no grind, chloro-bromide aerated atmospheric leach (85C), most sulphur conversion to elemental sulphur, leach temperature below sulphur melting point, novel membrane EW cell for dendritic copper production, precious metals leached in same process solution as copper, no cyanidation, no oxygen plant, possible environmental risk from oxidation of elemental sulphur and/or sulphide in leach residue.
 - NSC – fine grind, nitrogen species catalysis, medium to high temperature leach (125-165C), oxygen addition, temperature above sulphur melting point, conventional SX/EW, oxygen plant, chloride precipitation for silver recovery, thiosulphate leach for gold recovery, possible environmental risk from oxidation of elemental sulphur in leach residue.
 - Dynatec – medium grind with coal addition, medium temperature (150C) oxygen leach, temperature above sulphur melting point, leach residue flotation for unleached sulphide, recycle of sulphide to leach, elemental sulphur recovery, conventional SX/EW, precious metals extraction by cyanide leach of flotation tailings, oxygen plant, possible environmental risk from oxidation of elemental sulphur in leach residue.
8. Costs of process development will in general be high and only some of the processes are expected to survive the development process all the way through to a successful commercial plant.

Fig 1: Copper Concentrate Leaching Simplified Block Flow Diagram

