



# Copper recovery using leach/solvent extraction/electrowinning technology: Forty years of innovation, 2.2 million tonnes of copper annually

by G.A. Kordosky\*

## Synopsis

The concept of selectively extracting copper from a low-grade dump leach solution followed by stripping the copper into an acid solution from which electrowon copper cathodes could be produced occurred to the Minerals Group of General Mills in the early 1960s. This simple, elegant idea has resulted in a technology by which about 2.2 million tonnes of high quality copper cathode was produced in year 2000. The growth of this technology is traced over time with a discussion of the key plants, the key people and the important advances in leaching, plant design, reagents and electrowinning that have contributed to the growth of this technology. Some thoughts on potential further advances in the technology are also given.

## Introduction

A keynote paper for solvent extraction (SX) applications in hydrometallurgy should 'set the stage' for the papers that follow by discussing a commercially successful application of SX in hydrometallurgy. In addition the paper needs to discuss a complete metal recovery process for the simple reason that an SX process for metal recovery does not stand alone, it is always part of an overall metal recovery process. The SX process must be compatible with, and complimentary to, the metal leaching process that precedes it and the metal recovery process that follows. The paper should acknowledge that most of the advances in a metal recovery technology are made for economic reasons. This discussion of the leach/solvent extraction/electrowinning (L/SX/EW) process for copper recovery, considered by some to be one of the great advances in copper recovery technology of the past 100 years<sup>1</sup>, satisfies these criteria.

## Historical background

When the sulphuric acid copper L/SX/EW flow sheet (Figure 1) was put forth by the Minerals Development Group of General Mills in 1960 solvent extraction had been known for over 100 years<sup>2</sup>. It was used extensively on a very

small scale in analytical chemistry<sup>3</sup> and on a large scale for the recovery of uranium from sulphuric acid leach solutions<sup>4</sup>. General Mills had already developed and commercialized Alamine® 336 as an SX reagent for the recovery of uranium from sulphuric acid leach liquors<sup>5</sup> and believed that a similar technology for copper recovery would be welcome. However, an extensive market survey showed that the industry reception for copper recovery by L/SX/EW technology was almost hostile. The R&D director of a large copper producer predicted at an AIME annual meeting that there would never be a pound of copper recovered using solvent extraction and his comment prompted applause<sup>5</sup>.

Fortunately, the Minerals Development Group of General Mills, in the person of Joe House, Don Agers and Ronald Swanson, believed so much in the copper L/SX/EW process that they kept the development of this technology alive as a 'bootleg' project, that is, a project where the three individuals had other primary work duties and could only work on this project when they found time or on their own time. By late 1962 this group had identified and formulated an organic soluble molecule containing a hydroxy-oxime functionality as the reagent LIX®63. While LIX 63 had many of the properties required for a reagent to be successful in the proposed L/SX/EW flow sheet, LIX 63 was not compatible with the copper leaching process because it did not extract copper below pH~3<sup>6</sup>.

Technically this problem could be solved by neutralizing the acid leach liquor or by leaching oxide copper with ammonia, but neither solution was economical. A molecule that extracted copper well from typical dump leach liquors (pH ~1.8) had to be built. The reagent LIX 64, containing the ketoxime LIX

\* Cognis Corporation, Tucson, USA

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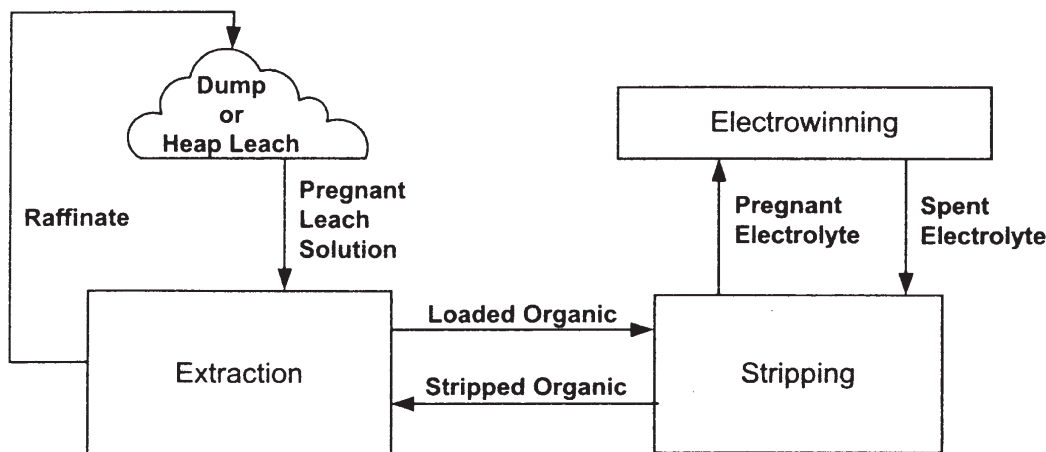


Figure 1— Conceptual leach/solvent extraction/electrowinning flow sheet

65 (Figure 2) and a catalytic amount of LIX 63, was introduced in 1965<sup>7</sup> and in March 1968 the first commercial copper L/SX/EW operation, the Bluebird plan of Ranchers Exploration and Development Corporation, came on line<sup>1</sup>.

### Copper recovery by L/SX/EX in 1968

In 1968 there were only two widely practiced copper leaching processes using dilute sulphuric acid. The first process, vat leaching of high-grade copper oxide ore followed by EW of copper from the leach solution, produced low quality copper cathode at relatively high cost. In 1968 the tonnage of high-grade oxide ores was decreasing and vat leaching was on the decline.

The second process, heap and dump leaching of low-grade oxide and/or sulphide ore followed by precipitation of low quality copper from the leach solution on scrap iron, was practiced on oxide ore that was too low-grade for vat leaching, or low grade sulphide ore that had to be mined in order to expose the underlying high grade sulfide ore. Copper recovered from leaching low grade copper ores was considered a bonus and little effort had been made to fully understand the leaching process or to maximize copper recovery. While some fundamental leaching studies had taken place<sup>8,9</sup>, on the whole leaching was a poorly practiced art and little had been done to make it a well-practiced science.

Solvent extraction for copper was not yet proven commercially so most copper companies were taking a wait and see attitude. Furthermore LIX 64, the only reagent available, had significant limitations with respect to extractive strength, metal transfer kinetics and copper/iron selectivity and it could only be used up to a maximum copper loading of about 3 g/l because of entrainment problems. These properties restricted copper leach solutions which could be effectively treated by SX using LIX 64 to  $\leq 3$  g/l Cu at a pH  $\geq 1.8$ .

In 1968 the copper industry as a whole did not believe large quantities of high quality copper could be produced by hydrometallurgy and at the time the Ranchers plant came on line, expectations for the eventual success of copper L/SX/EW technology were rather modest.

### Ranchers' Bluebird sulphuric acid leach/solvent extraction/electrowinning plant

Ranchers leached run of mine copper oxide ore (> 0.5% Cu) placed in a sealed canyon in 20-foot layers (heaps) by distributing dilute sulphuric acid over the fresh ore via spray emitted from needle valves with pipes and needle valves placed to ensure complete coverage of the ore. New heaps were built over old heaps. Pregnant leach solution flowing from the bottom of the heap was collected in a pond created by placing a dam downstream from the leach area. The Bluebird copper SX plant was built similar to existing uranium SX plants with tall, single baffled mixers and long narrow settlers. Dispersion exiting the mixer was pumped to the opposite end of the settler and the phases flowed back toward the mixers.

In electrowinning rich electrolyte with ~36 g/l Cu, 3 g/l Fe and 145 g/l H<sub>2</sub>SO<sub>4</sub> entered one end of the EW cells and spent electrolyte with ~32 g/l Cu and 151 g/l H<sub>2</sub>SO<sub>4</sub> exited the other end. Cathodes weighing 60 kilograms were grown on copper starter sheets at a current density of about 180 A/m<sup>2</sup> with a current efficiency of 80 to 85%. The anode was 6% Sb in Pb.

Design production at Ranchers was 30,000 pounds of copper daily. In its first fiscal year of operation, July 1968–June 1969, the Bluebird plant produced 9 million pounds of copper (82% of design), a remarkable achievement for a metallurgical plant using new technology. By later adding only rectifier capacity the plant often exceeded its design production by 50%.

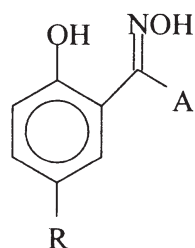
Ranchers' Bluebird plant proved that L/SX/EW technology could produce large quantities of good quality cathode copper on a consistent day to day basis at a profit<sup>1</sup>. This raised the awareness and sparked the interest of the industry in copper L/SX/EW. Improvements in the technology quickly followed from many sources including consultants, copper producers, engineering companies, chemical companies and metallurgical testing laboratories.

### Improvements in copper L/SX/EW technology

#### Solvent extraction reagents

The first improvement in copper SX reagents came when LIX

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REAGENT	R	A	TYPE
LIX 65	C <sub>12</sub> H <sub>25</sub>	C <sub>6</sub> H <sub>5</sub>	Ketoxime
LIX 65N	C <sub>9</sub> H <sub>19</sub>	C <sub>6</sub> H <sub>5</sub>	Ketoxime
SME 529, LIX 84-1	C <sub>9</sub> H <sub>19</sub>	CH <sub>3</sub>	Ketoxime
LIX 860-1, LIX 622	C <sub>12</sub> H <sub>25</sub>	H	Aldoxime
P1, LIX 860N-1	C <sub>9</sub> H <sub>19</sub>	H	Aldoxime

Figure 2—General structure of oxime molecules used for copper recovery

64N was added as makeup to the Ranchers plant in late 1968. LIX 64N had greater extractive strength, faster kinetics, faster phase separation, lower entrainment, increased copper/iron selectivity and lower viscosity than LIX 64<sup>10</sup>. These improved reagent properties broadened the range of copper leach liquors which could be successfully treated by solvent extraction, for less staging thereby reducing the capital cost of the SX plant, and lowered operating costs by decreasing organic losses and tankhouse bleeds. LIX 64N is LIX 65N (Figure 2) with a catalytic amount of LIX 63.

In 1968 Ashland Chemical introduced Kelex® reagents along with the idea of using varying amounts of modifier, either nonylphenol or isodecanol, to facilitate the stripping of copper from the loaded reagent with normal tankhouse electrolytes<sup>11,12</sup>. Kelex reagents have not been used commercially for copper SX, but the use of modifiers to shift the extraction ↔ stripping equilibrium of copper extractants represents a significant, widely used advance in copper SX.

Shell International Chemicals brought the reagent SME®529 (Figure 2) to the market in the mid-1970s as an alternative to LIX 64N. This reagent found only limited commercial use because the poor properties of the side products from the manufacture of this reagent overrode the very good properties of the extractant molecule in wide use today.

At ISEC '74 Birch reported the reagent P1 (Figure 2) from Acorga Ltd had rapid kinetics, excellent Cu/Fe selectivity and fast phase separation<sup>14</sup>. However, P1 was such a strong copper extractant that efficient stripping required nearly 250 g/l sulphuric acid, an acid content not compatible with normal EW practice. In 1977 the Acorga P-5000® series of reagents was described<sup>15,16</sup>. These reagents combined P1 with various amounts of nonylphenol to give reagents having tailored extraction ↔ stripping properties. These modified aldoxime reagents brought a significant advance to copper SX because they allowed solutions with a high copper content and/or a low pH to be effectively treated in 2 instead of 3 or 4 extraction stages.

In 1979 the tridecanol modified aldoxime reagent LIX 622 (Figure 2), was made available by the Henkel Group which had purchased General Mills Chemicals in 1977. LIX 622 was the first tridecanol modified reagent to be commercialized when the Pinto Valley copper SX plant came on line in 1981. Tridecanol is still a widely used modifier in copper SX reagents.

Aldoxime/ketoxime blends were introduced in 1982 by Henkel as the LIX 860 reagent series. This reagent series combines the fast kinetics and extractive strength of the aldoximes with the stability and good physical performance

of the ketoximes, without the detrimental properties of added modifier<sup>17</sup>. The addition of LIX 860-1 (Figure 2) to existing plants using LIX 64N allowed these plants to quickly upgrade their plant performance and flexibility if needed or desired. Today aldoxime/ketoxime blends are widely used in copper SX.

Henkel purchased the SME 529 technology from Shell in late 1984 and 2 years later, using a new manufacturing process, began producing LIX 84-1, a much improved version of SME 529 (Figure 2). LIX 84-1 replaced LIX 64N and LIX 65N in the LIX Reagent line and led to the LIX 900 reagent series of LIX 84-1/LIX 860-1 blends.

The use of hindered, high molecular weight alcohols and esters as modifiers was reported in 1986 with the claim that ester modifiers increase both Cu/Fe selectivity and oxime stability when compared to other modifiers<sup>18</sup>. Since then the ester modified reagents such as M5640 and LIX 664N have become the most popular of the modified reagents.

Improvements in reagent properties for the extraction of copper from dilute sulphuric acid leach solutions are summarized in Table I. These improvements have come about for 3 reasons.

- New molecules: LIX 65N, SME 529, P-1 and LIX 84-1 are examples
- Improved processes to produce cleaner reagents: LIX 65N and LIX 84-1 are examples
- Manipulation of reagent properties: modified aldoximes and aldoxime/ketoxime blends are examples.

There are two distinct classes of modern extractants: ketoximes and aldoximes. A general comparison of their properties as well as mixtures of the two is given in Table II.

Ketoximes are moderately strong copper extractants which operate best when the leach liquor is relatively warm and the pH is ~1.8 or above. Modified aldoximes have good metallurgical properties even at low temperatures and low pH. The properties of aldoxime/ketoxime blends reflect the ratio of the components. Today the metallurgist can select the best reagent or reagent blend for his/her leach liquor, plant

Property	1965	1970	Late 1970s	Today
Extractive Strength	Moderate	Moderate	Strong	Tailored
Cu/Fe selectivity	Fair	Good	Good	Excellent
Kinetics	Slow	Moderate	Fast	Fast
Stability	Excellent	Excellent	Good	Very good
Crud generation	Moderate	Low	Moderate	Low
Versatility	Poor	Marginal	Good	Excellent

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design and operating conditions. For examples, one plant used an aldoxime/ketoxime blend of 55/45 when the pH of the leach liquor was ~1.5, but, today the plant adds a 50/50 blend because the pH of the leach liquor has risen to ~1.7. Metallurgical performance, entrainment, crud generation, mixer stability, price and the performance of the various reagents in plants having similar design and/or operating with a similar leach liquor should all be considered when making a reagent choice.

### Leaching

Once solvent extraction proved to be a cost-effective way to purify and concentrate copper from leach liquors, copper producers began to regard leaching as a much more important source of copper. Two early advances in leaching include the distribution of large drops of leach solution over the ore at Baghdad in 1970<sup>19</sup> and the use of drip irrigation by Johnson Camp in 1976<sup>20</sup>. These improvements resulted in decreased water consumption, increased temperature in the heaps or dumps and higher copper recovery.

The 'Thin Layer' (TL) acid cure leaching process reported in 1978 is to date the single greatest advance in copper leaching<sup>21</sup>. The first plant practice of TL leaching for copper was in 1980 at Sociedad Minero Pudahuel (SMP)<sup>22</sup>. SMP obtained high copper recovery from both the oxide and sulphuric portions of their ore, low soluble silica in the pregnant leach liquor, and an overall water/acid balance to give a zero discharge plant. The important role of bacteria in leaching metal sulphides had been known<sup>9</sup> and some of the practical aspects of biological leaching had been discussed<sup>23</sup>. However, copper recovery from a high-grade sulphide ore by bacteria-assisted heap leaching was not considered economically viable until SMP showed that the total copper recovery from the chalcocite/bornite portion of their mixed oxide sulphide ore could reach 85% by leaching the tails from their TL operation for another 45 days<sup>22</sup>. Inspiration Copper in Arizona was testing with good results a similar technique called 'ferric cure' on heaps of 100% minus four inch mixed oxide/sulphide ore<sup>8</sup>.

In 1984 BHAS began agitation leaching copper matte from a lead blast furnace with a sulphuric acid leach solution having about 1 molar chloride ion<sup>24</sup>. This leaching system is reported to be effective for leaching copper sulphide ores and concentrates. Also in 1984 Sunshine Mining company installed a batch plant to pressure leach copper sulphide concentrate with sulphuric acid containing a catalytic amount of sodium nitrite<sup>25</sup>.

In the late 1980s low-grade chalcopyrite dumps at Toquepala were wetted with 10 g/l H<sub>2</sub>SO<sub>4</sub>. Naturally occurring bacteria multiplied, oxidized the sulphide minerals and warmed the dumps. When copper SX started in 1995 the initial flush of copper from these dumps was much greater than anticipated and copper recovery over the first five years has been much higher than expected based on the leaching history of other low-grade chalcopyrite dumps.

Forced aeration to increase bacterial activity in heaps and dumps was field tested in the 1970s and successfully commercialized in the mid to late 1990s<sup>26</sup>. Of particular note is the Quebrada Blanca operation in Chile where bacterially assisted heap leaching of chalcocite, aided by forced aeration, is successfully practiced at an elevation of 4,400 metres<sup>27</sup>. The leaching of high-grade chalcocite ore in an autoclave at relatively low temperature and pressure was commercialized at Mt. Gordon in mid-1998 by Western Metals Copper Ltd<sup>28</sup>.

'From an poorly practiced art to a near science' describes the changes in leaching practice since the late 1960s. Heaps and dumps are constructed to retain heat, wet all the ore evenly, and for sulphide ore, to encourage air circulation through the dump or heap. Advances in heap leaching include blasting techniques which size ore to optimize copper recovery, crushing to the optimum size, agglomeration techniques, agglomeration aids, curing methods, heat retention and bacteria augmentation. Copper recoveries of 85% are being reported at several oxide heap operations and many chalcocite heap leaches report 75% to 80% copper recovery.

Sulphuric acid leach solutions treated successfully by copper SX range from <1 g/l Cu up to about 35 g/l Cu with a pH range of ~0.8 to ~2.5. Leach solutions contain a variety of impurities at various concentrations depending on the ore, available water and evaporation rate. The SX plant must produce an electrolyte from which Grade A copper can be plated and most plants do, some from very difficult leach solutions. For example, the Michilla plant in Chile treats a leach solution having 55 g/l chloride while Lomas Bayas in Chile has treated a leach solution having 35 g/l nitrate and 15 g/l chloride. Both plants consistently produce high quality copper.

### Electrowinning

In 1968 Ranchers installed flotation cells to remove entrained organic from the pregnant electrolyte resulting in improved copper quality. In the late 1970s Anamax installed an electrolyte filter to clean the electrolyte of both solids and organic. A major breakthrough in EW came when Baghdad cathode was registered on the Comex in 1975 followed several years later with the registration of Anamax cathode on the London Metal Exchange.

Other important EW developments include: plating hard bright copper consistently onto starter sheets at 320 A/m<sup>2</sup><sup>29</sup>, the addition of cobalt in the electrolyte to reduce lead anode corrosion<sup>30</sup> and the use of water-soluble polymers as smoothing agents. Rolled anodes of Pb-Ca and Pb-Sr-Sn are now the anode of choice because of their dimensional stability, lower rate of corrosion and the fact that a node cathode spacing in the cell is slightly less than when a cast anode is used<sup>31</sup>. The use of a cathode press to straighten 2-day cathodes grown on copper starter sheets results in higher current efficiencies and improved copper quality<sup>32</sup>.

Capital Wire and Cable plated full size cathodes on stainless steel blanks in the early 1970s while Magma Copper was the first Cu EW tankhouse to use the CRL ISA Process

Table II

#### Properties for reagents based on ketoximes, modified aldoximes, and ketoxime-aldoxime mixtures

Property	Ketoxime	Aldoxime	Mixtures
Extractive strength	Moderate	Strong	Customized
Stripping	Very good	Reasonable	Customized
Cu/Fe selectivity	Excellent	Excellent	Excellent
Copper kinetics	Very good	Very fast	Fast
Phase separation	Fast	Fast	Fast
Stability	Excellent	Very good*	Very good
Crud generation†	Low	Variable	Low

\*Dependent upon the particular modifier used

†Dependent upon the leach liquor and modifier

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where full size cathodes are grown on stainless steel blanks and then mechanically stripped. Plating copper on stainless steel blanks improves copper quality and increases current efficiency. The use of a manifold to evenly distribute electrolyte to every cathode in a cell was installed at Magma Copper in the late 1980s and was a key factor in their ability to produce LME quality copper at current densities up to 320 A/m<sup>2</sup><sup>33</sup>.

A modern copper EW tankhouse coupled with copper SX achieves 93–95% current efficiency while producing 60% to 80% more copper per unit of tankhouse area than the early EW tankhouses. Full size cathodes are deposited on stainless steel blanks at 240–320 A/m<sup>2</sup> from a solution containing 32 to 37 g/l Cu and 160 to 180 g/l H<sub>2</sub>SO<sub>4</sub>. Most large tankhouses mechanically strip the copper from the blanks while most small tankhouses combine some automation with hand stripping. The electrolyte stream is cleaned by column flotation followed by filtration through garnet sand and anthracite. Special grades of guar are used as smoothing agents, and acid mist suppressants, either chemical, mechanical or a combination of both, are common. Most EW tankhouses coupled with a copper SX plant consistently produce Grade A copper.

### Mixer settler design

In 1972 General Mills suggested the addition of one or more properly designed 'picket fences' in settlers to distribute the dispersion exiting the mixer evenly across the full width of the settler<sup>34</sup>. This results in improved settler throughput and much lower entrainment.

A major advance in mixer settler design is the low profile concept from P. Paige of Holmes and Narver<sup>35</sup>. The mixer consists of several shallow boxes separated by over/under baffles. A pumping impeller is used in the primary mix box while axial impellers designed to maintain the dispersion are used in the secondary mixers. The settlers have a length to width ratio  $\leq 1$  and are built on the ground, usually at grade. The advantages of this design included lower capital, high mixer efficiency, slower linear flow down the settler resulting in less entrainment, and an overall smoother operation. Most copper SX plants built in the past 25 years are of the low profile design. Typically, copper SX plants are designed so that the dispersion exits the mixer directly into the mixer end of the settler with the flow of the phases away from the mixer. Recently several plants have been built where the dispersion is carried to the opposite end of the settler by a side launder as this design offers the potential to reduce capital.

A key improvement in mixer design that reduces entrainment is the swept vane impeller. The Lewis type baffled settler<sup>36</sup> and the Krebs design<sup>37</sup> while commercialized are not considered standard practice in the copper industry. Two recent innovations in mixer design are very promising, the Outokumpu Vertical Smooth Flow mixer<sup>38</sup> and the new Lightnin mixer system at ASARCO Silver Bell. Both have relatively small primary mixers and much larger secondary mixers. It is claimed these mixer systems give lower entrainment and less crud generation because the dispersion spends less time in the highly agitated primary mixer and more time in the more gently agitated secondary mixers. Reagent losses at Silver Bell are among the lowest in the industry suggesting the claims have merit.

Other important design innovations include well-designed coalescers on the loaded organic stream, filter presses for crud treatment, clay treatment<sup>39</sup> to keep the

organic clean and large flotation settling tanks that recapture organic entrained in the raffinate.

### Installed production capacity for sulphuric acid copper L/SX/EW

The installed capacity for copper production by sulphuric acid L/SX/EW is given in Table III. Note that from a rather modest beginning in 1968 the installed capacity for copper production by L/SX/EW is today about 2.8 million tonnes annually. This represents about 20% of the primary copper produced. The major reason for the large increase in L/SX/EW capacity is its lower cost, both capital and operating, when compared to the traditional flotation/smeltering route. An important feature of the economics is that both large and small plants can achieve low costs. For example, the Dos Amigos operation in Chile (10,000 MT Cu/year) has about the same cash cost to produce copper as the Zaldivar operation in Chile (140,000 MT Cu annually). In addition EW copper from copper SX plants obtains a premium in the market-place over most cathode copper produced by the flotation/smeltering route. Furthermore, L/SX/EW technology allows plants to obtain copper at a low incremental cost from low-grade overburden that needs to be mined but otherwise would not be processed. Copper SX technology also has great flexibility allowing plants to achieve design production under a variety of conditions. Finally, copper L/SX/EW provides a home for sulphuric acid produced by smelters.

Today there are more than 55 locations (China excluded) with SX plants recovering copper from dilute sulphuric acid leach solutions. The number of SX trains and the complexity of the SX/EW installation range from the simple 2E, 1S single train installation at Mt. Cuthbert in the Australian outback producing 5,500 M tonnes Cu annually, to the Phelps Dodge L/SX/EW complex at Morenci, Arizona, where about 16,500 m<sup>3</sup>/h of heap and dump leach liquors are treated in four separate, multi-train, 1E, 2E, 1W, 1S stage SX plants placed strategically on the property. The SX plants at Morenci feed 3 EW tankhouses that produce a total of about 365,000 M tonnes Cu annually. Copper SX mixer-settlers range in size from the very small treating about 100 m<sup>3</sup>/h of leach solution, to large modules treating about 2,000 m<sup>3</sup>/h of leach solution.

### Future improvements in L/SX/EW technology

There may be incremental advances in today's leaching practice for oxide and chalcocite ores. However, the most abundant copper mineral is chalcopyrite and heap leaching this mineral with dilute sulphuric acid gives recoveries of only 25 to 30%. Obtaining high recoveries by heap leaching

Table III

#### Installed capacity for copper production by sulphuric acid L/SX/EW

Year end	Installed capacity (MT Cu annually)
1970	11.250
1975	108.912
1980	255.122
1985	355.954
1990	800.857
1995	1,563.205
2001	2,844.200

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chalcopyrite with dilute sulphuric acid would be a truly revolutionary advance that would change the copper industry dramatically. There is ongoing work in this area and, while there has been some progress, much work remains.

In recent years there has been significant progress in leaching copper sulphide concentrates as an alternative to smelting<sup>40</sup>. Both pressure leaching (without nitrite catalysis) and bacteria-assisted leaching in stirred tanks have been demonstrated for copper sulphide concentrates in pilot plants and small demonstration plants and both technologies are likely to be commercially installed within 2–4 years.

While revolutionary improvements in the properties of reagents for the extraction of copper from sulphuric acid leach solutions are not likely, small improvements in the blending of reagents and in the processes to produce reagents may come. The reagents of today are very good and the investment required to produce better reagents would not likely pay the needed return.

Increases in the current density at which high quality copper can be plated will be incremental with the current EW cell design. A new cell design that plates high quality copper at high current density from low grade solutions has recently emerged<sup>41</sup> and if certain problems can be solved this design could represent a significant advance in copper EW technology.

## Conclusions

By any standard of measurement L/SX/EW technology has made an important contribution to the copper industry. Initially, the availability of LIX 64N and the success of Ranchers sparked interest to improve leaching and electrowinning techniques. Since that time a synergistic push-pull mechanism has emerged where an improvement in one aspect of the technology drives improvement in the other aspects. This synergistic push-pull mechanism will continue to advance copper L/SX/EW technology, but not likely at the pace of the past 34 years. The close working relationships between suppliers, engineering companies and copper producers that developed over the years have also contributed significantly to the improvements in the technology and it is important that these relationships continue.

The most fitting way to close this paper is to quote two early believers in copper L/SX/EW technology. Maxie Anderson, president of Ranchers, at the dedication of the Bluebird copper L/SX/EW plant said: 'Not often does a small company have the opportunity to change the course of an industry and add to new technology...'. In 1970 Ken Power closed his paper describing the operation of the Bluebird copper L/SX/EW plant with the words: 'The applicability of liquid ion exchange to the treatment of dilute impure copper solutions has been irrefutably demonstrated, both technically and economically. The field of application in the hydrometallurgical treatment of copper minerals and products appears limitless<sup>1</sup>. Today, more than 3 decades later, these prophetic words ring with clarity.

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