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- → Significant advancements have been achieved with both the stainless steel cathode technology and the electrode handling equipment used in copper tankhouses.

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For more:
isakidd@glencore.com.au
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Copper Refinery Modernisation, Mopani Copper Mines Plc, Mufulira, Zambia

Maambo Chooye[1], Rakesh Patel[1], Addin Pranowo[2] and Brendan O'Rourke[3]*

[1]Mopani Copper Mines, Mufulira, Zambia
[2]Glencore Technology, Townsville, Australia
[3]Glencore Technology, Brisbane, Australia

**Corresponding author: brendan.orourke@glencore.com.au*

The electrolytic refining of copper has been conducted at Mufulira, Zambia, since 1939. The original refinery has been upgraded and expanded since then to match the output of anodes produced at the Mufulira, Luanshya, and Nkana smelters at various times; however, by the end of 2012, it was recognised that customer expectations regarding–cathode physical quality and chemical purity have increased due to the introduction of new copper refining technologies. In June 2013, Mopani Copper Mines Plc (MCM) committed to the modernisation of the copper refinery that included the conversion of the existing refinery to the ISAPROCESS™ technology, installation of electrode handling equipment, upgraded electrolyte circulation systems, and upgraded process control systems. This paper describes the equipment, technologies and new operational practices that constitute the Mufulira Refinery Upgrade Project. All activities have been progressively completed since late 2014 and have culminated with the registration of a new London Metals Exchange cathode brand, MCM2, in July 2017. The MCM Refinery is the first copper electrorefining plant in Africa to utilise the ISAPROCESS™ technology.

INTRODUCTION

Copper has been electrolytically refined in Mufulira, Zambia for over 75 years. The original refinery has been expanded several times and one part of the refinery was expanded to conduct commercial-scale electrowinning operations. These operations included in-situ leaching, vat leaching, and heap leaching of oxide ores. A dedicated solvent extraction plant was associated with each leach operation.

The primary objective of the Refinery Modernisation Project was to ensure that current and future customer expectations could be fully satisfied, and to implement productivity improvements, whilst allowing the refinery to have the flexibility to source anodes with higher impurity levels than currently received. This necessitated a change in the refining technology used by Mopani Copper Mines Plc (MCM).

MCM selected the ISAPROCESS™ technology due to its extensive record of converting starter-sheet refineries to permanent stainless steel cathode plates. At the same, MCM also took the opportunity to upgrade and modernise its electrode handling systems, electrolyte circulation systems and process control systems.

Owing to the requirement for the existing refinery to maintain copper production operations at full capacity, the upgrade activities were conducted progressively over a four-year period. The constructions activities are described below in more detail. The operational improvements since completion of the project are also described in detail.

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Southern African Institute of Mining and Metallurgy

PROCESS SELECTION

Layout

Various combinations of cell house layout and design have been implemented in ISAPROCESS™ copper refineries. MCM was constrained in some cases due to the requirement to maintain full copper cathode production capacity during the modernisation activities. In particular, this meant that the new electrode handling machines had to be located in areas that were not being used for existing production activities. The location of anode receipt from the smelter was fixed by the existing transport infrastructure.

Design Criteria

The principal design objectives for the project were:

- Long-term production forecasts;
- customer requirements;
- productivity improvement;
- upgrade of electrolyte circulation systems;
- future expansion options.

Long-term production forecast

MCM is upgrading the existing Mufulira Mine and expects to complete the new Synclinorium Mine and Concentrator Project in 2019. When combined with external concentrate feed treatment at the MCM smelter, this will enable the Mufulira Smelter to increase production to 225 000 tonnes per annum. The modernised refinery production capacity matches this requirement.

Customer requirements

MCM has been producing copper cathode marketed under the London Metal Exchange (LME) Registered Brand MCM. Cathode produced by the modernised refinery is now marketed under the LME Registered Brand MCM2. The cathode bundle being produced now has many advantages over the previous style. It is compact, easier to handle and transport and no longer has the protruding starter-sheet loops associated with starter-sheet cathode.

Productivity improvement

Using starter-sheet technology, MCM was operating four tank houses plus a starter-sheet production aisle with-in their refinery complex. Glencore Technologies experience with ISAPROCESS™ copper refinery conversions conducted over the past 30 years was that conversion to stainless steel cathode plate technology achieved direct productivity improvements of 25% to 30% when compared with starter-sheet technology. In the specific MCM case, this has allowed MCM to reduce the operational footprint to three tank houses, with an associated reduction in the number of operating overhead cranes, refining cells, and, importantly, copper inventory.

Further productivity improvements have been made in the electrode handling task. The elimination of starter sheets has removed all aspects of starter-sheet production – starter-sheet production cells, manual stripping, sorting, and preparation activities, loop production, hanger bar assembly, manual cell loading, alignment activities and replacement of falling cathode due to broken loops. The introduction of the ISAPROCESS™ permanent stainless steel cathode system requires a dedicated cathode stripping machine (CSM) to perform cathode stripping operations. The CSMs selected at MCM are capable of fully automatic operation and eliminate all steps that were performed manually. At the same time, MCM elected to introduce a fully automated anode preparation machine (APM), anode scrap washing machine (ASWM), and upgraded its overhead refinery cranes to suit the new electrode handling machines.

Upgrade of electrolyte circulation systems

With the expected increases in copper production intensity, it was determined that the existing circulation systems required additional circulation capacity and improved process control. At the same time the refinery circulation equipment configuration was changed so that each tank house now has its own, independent circulation system. All piping associated with the refining cells has been upgraded and the ability to collect decant solution from each refining cell during anode change operations has been implemented. The reagent dosing system was replaced for each tank house with a system that has the ability to prepare and dose thiourea, glue and salt. Automated process control has been implemented for all circulation system equipment via the introduction of a SCADA PLC-based system.

Future expansion options

The current MCM refinery building has five individual tank houses plus a dedicated starter-sheet section. The design, specification and placement of all electrode handling equipment will allow MCM to expand its refinery production to five tank houses without the need to purchase additional anode handling equipment.

Final Process Selection

The modernisation of the MCM copper refinery was implemented with the following items:

- introduction of the ISAPROCESS permanent cathode plate technology;
- replacement of starter-sheet preparation machines with automated cathode stripping machines;
- introduction of automated anode scrap washing machine and automated anode preparation machine;
- introduction of automated anode and anode scrap transfer system;
- anode mould design was upgraded to match new anode dimensions;
- total replacement of electrolyte circulation system piping;
- installation of dedicated cell decant electrolyte piping system;
- replacement of fixed-speed circulation pumps with variable-speed drives;
- replacement of all reagent dosing equipment;
- partial replacement of overhead cranes;
- upgrade of anode and cathode lifting bales on the refinery overhead crane;
- installation of a SCADA PLC-based process control;
- installation of cell voltage monitoring system;
- implementation of an intermediate bar-based cell top furniture system;
- installation of new electrolyte circulation system tanks in Tank house Five;
- replacement of 336 refining cells in Tank House Five.

PROCESS DESCRIPTION

Modernised Refinery Operating Statistics

Table I shows the key operational statistics for the modernised refinery.

Table I. Operating statistics for new refinery.

Capacity	225 000 t per annum
Cells	1320
Electrodes per cell	36 cathode / 37 anode
Electrode pitch	100 mm
Cathode deposition area, per side	0.82 m^2
Maximum anode mass	320 kg
Maximum cathode mass	60 kg
Anode cycle	18 days nominal
Cathode cycle	2 crop or 3 crop
Current density	305 A/m^2
Electrolyte circuits	3
Number of cranes	6

Refinery Layout

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The existing MCM Refinery design is typical for the era in which it was built. Overhead refinery cranes from that era had very slow operating speeds hence the design objective was to minimise the length of crane runs. Crane rail heights were also set as low as possible to reduce lifting and lowering times for electrodes. This lead to refineries being built with multiple aisles, short crane runs with a low operating height over the electrolysis cells. Movement of material was best managed by having a common centrally located aisle running the length of the refinery building. Industrial standard forklifts were also not common at the time so rail was used as a method for moving anodes, anode scrap and copper cathodes.

Owing to the existing layout, all of the new electrode handling machines can only be located in the central common aisle. This led to the situation where anodes and anode scrap need to be conveyed up to 120 m if only one APM and one ASWM unit are installed. By working with the supplier of the APM and ASWM, an innovative ground-running transfer car system for carrying anodes and anode scrap was specially developed for each machine. All of the electrode handling machines are designed to be serviced by forklifts.

Figure 1. New overhead crane with drip tray carrying cathode plates.

Electrode Handling Equipment

Anode preparation machine

Anodes are received from MCM's copper smelter via rail and forklift. Anodes are loaded to the APM by forklift for weighing, blade pressing, lug-offset pressing and contact milling. Contact milling is used to ensure that anodes hang vertically in the cell and ensure best possible current distribution in the refining cells. The anodes are then transported in loads of 36 anodes to the appropriate tank house using the anode transfer car system. The APM was supplied by MESCO, Japan.

Anode transfer cars

A transfer car system is used to move anodes and anode scrap with-in the refinery building. Each transfer car runs at ground level and carries 36 pieces of anode or anode scrap to or from the respective APM or ASWM. Each transfer car services nine fixed set-down or pick-up positions located across the length of the refinery building. The Anode transfer car system was supplied by MESCO, Japan.

Cathode stripping machines

Three medium speed CSMs have been installed at MCM. One CSM is installed in each operating tank house; however, each CSM has the capacity to service the electrodes from the two bays in each tank house. The CSMs have been specially designed to interact with manually operated and low clearance overhead cranes. This means that conveyors are used to transfer cathode plates instead of fast-moving trolleys. This eliminates the possibility of a crane bale to trolley collision. A forklift is used to remove the finished cathode bundles to the product despatch area. The wash water used to remove electrolyte from the cathode deposits is heated using electric heaters. The wash water system is designed for future conversion to steam heating. The CSMs were supplied by MESCO, Japan.

Anode scrap washing machine
Anode scrap is moved from the refining cells by overhead crane and then conveyed to the ASWM via the transfer car system. In the ASWM, the scrap is washed to remove any adherent slimes and then formed into bundles for forklift removal. Anode scrap is returned to the copper smelter. The ASWM was supplied by MESCO, Japan.

Overhead crane upgrade
The change in refinery electrodes, electrode pitch and cell-top furniture necessitated that new anode and cathode plate bales were required for the overhead cranes. At the same time, MCM decided to replace four of the six existing refinery cranes. MCM utilises crane transfer cars located at the end of each tank house. This allows the overhead cranes to be moved to another aisle when needed, thus reducing the overall number of cranes required in the refinery. The new cranes and lifting bales were designed and supplied by DEMAG, South Africa.

Electrolyte Circulation
Many parts of the existing circulation systems were not suitable for the increased operating intensity associated with the ISAPROCESS™ technology. A higher and more consistent cell electrolyte flowrate was the major change required. This meant that all electrolyte piping was upgraded, together with the associated circulation pumps. The use of variable-speed pumps was required so that a responsive flow control scheme could be implemented. The electrolyte is distributed to the cells by direct pumping without an intermediate head tank. Owing to the introduction of the thiourea reagent to replace Tembind, the existing reagent dosing systems were also replaced.

Figure 2. ISAPROCESS™ permanent stainless steel cathode plates in service.

Process Control and Monitoring
To ensure the correct electrolyte conditions for electrolysis at the higher operating intensities, improved process control of the operation was required. This has been achieved by implementation of a SCADA-based PLC system for the electrolyte circulation. The Siemens PLC-7 system was used for the SCADA configuration.

Refinery Cells
As most of the existing refining cells were retained, the dimensions of the new stainless steel cathode plates were matched to the internal cell dimensions. The dimensional design of the anode was changed to match the new cathode plate dimensions. Owing to the inherent straightness of the stainless steel cathodes, the electrode pitch in the cell was able to be reduced to 100 mm, which provides reduced power consumption when compared with the starter-sheet design. The cathode plates were designed and supplied by Glencore Technology, Australia.

The upgrade of the electrolyte circulation system required changes to the electrolyte feedpipe for each cell. At the same time, an individual cell flow-control device was included in the new piping design. New cells were installed in Tank house Five to allow for full implementation of the decant collection system.

It was necessary to change all cell-top furniture to an intermediate bar design. The end cell busbars on all sections required modification to suit the ISAPROCESS™ system. The additional busbar elements and intermediate bars were designed and supplied by Copalcor, South Africa.

CONSTRUCTION

In all cases, the scheduling of construction activities was dictated by cathode production requirements. With four tank houses still available for production, each of the three modernised tank ouses was consecutively taken off-line for refurbishment over a two-year period. At the same time, MCM was forced to curtail production during 2016 due to power supply restrictions in place in Zambia.

The major construction milestones are listed below:

Jan–May 2014	New end cell busbars designed and installed
July–Dec 2014	Preparation of electrode handling machine areas
Oct–Dec 2014	Installation of electrode handling machines – TH1 & TH4 CSM's
Feb–March 2015	Installation of electrode handling machines – APM, ATS
May 2015	Installation of electrode handling machines - TH5 CSM
June–Aug 2015	Replacement of reagent system, piping and pumps – TH4
May–Aug 2016	Installation of new overhead cranes
Feb- July 2016	SCADA and cell voltage monitoring installed
Mar–Dec 2016	New circulation system for TH5 installed
May–Oct 2017	Installation of new cells – TH5
May–Nov 2017	Replacement of piping and pumps – TH 1
November 2017	Replacement of piping TH5

COMMISSIONING

MCM formed a dedicated commissioning team to ensure that the transition between the two operating systems was performed safely and in step with the completion of construction/installation activities. A major emphasis was placed on training across all disciplines: metallurgy, operations and maintenance. At the same time, the operational requirements and testing to obtain LME registration for the new cathode were completed.

The key commissioning milestones are listed below:

Jan–Feb 2015	Operations and maintenance training program completed at CRL Australia and PASAR, Philippines
March 2015	Full commissioning of CSM TH4, APM, ATS, ASWM and TH4 circulation systems

Apr–July 2015	Full conversion of TH4 for first LME registration testing program
Jan–Dec 2016	Second LME registration testing period – TH4
June 2016	Full conversion of TH1 and commissioning of CSM TH1, CSM TH5
June–Nov 2016	Progressive commissioning of new refinery overhead cranes
June 2017	LME registration granted for MCM2 brand
October 2017	Central control room operational for SCADA and cell voltage monitoring systems
October 2017	Full conversion of TH5 and commissioning of TH5 circulation system
October 2017	Starter-sheet oOperations ceased

Commissioning engineers were supplied from MESCO, DEMAG and Glencore Technology for the electrode handling equipment. Specific ISAPROCESS™ training services and process engineers were also provided by Glencore Technology. MCM also retained the services of two expatriate electrode handling machine specialists to provide on-site training.

PRODUCTION AND OPERATIONAL IMPROVEMENTS

Table II details the improvements in several refinery production performance indicators since the conversion of the refinery to the ISAPROCESS™. The level of improvement achieved is consistent with the levels foreseen during the feasibility study phase of the project.

***Table II. Cathode purity** improvement – ISAPROCESS vs conventional.*

Impurity (ppm)	Conventional			Full ISAPROCESS	Note
	2014 average	2015 average	2016 average	2017/8 average	
S	3.74	6.29	4.93	4.43	Similar
Pb	1.50	1.81	1.42	0.53	Improved
Ni	1.19	1.27	0.70	0.58	Improved
As	1.24	1.48	1.27	0.50	Improved
Bi	0.43	0.41	0.26	0.20	Improved
Sb	0.36	0.51	0.54	0.47	Similar
Se	1.07	1.24	0.84	0.28	Improved
Ag	6.48	6.20	5.35	5.95	Similar
Sn	0.28	0.24	0.31	0.25	Similar
Te	0.45	0.43	0.46	0.31	Improved
Zn	0.56	0.46	0.48	0.418	Similar
Fe	<2	<2	0.48	0.35	Similar

Table I shows the long-term improvement in copper cathode impurity levels for the common cathode copper impurities. These levels easily comply with the requirements for LME Grade A copper cathode. At least four different mechanisms for cathode impurity exist in an industrial-scale copper electrorefinery. Each mechanism and the associated impurities are briefly described below with reference to Mopani's specific anode impurities:

- inclusion of slimes in cathode deposit: indicators are lead, selenium, arsenic, bismuth, tellurium and antimony;
- occlusion of electrolyte in cathode deposit: indicators are nickel, iron and arsenic;
- electrolytic codeposition: indicator is silver;
- precipitation on cathode deposit surface: bismuth, antimony, tellurium and arsenic.

Impurities associated with slimes inclusion have shown the greatest improvement. The inherent straightness of the permanent stainless steel cathode plate means the probability of a slimes particle making contact with the cathode deposit during electrolysis is significantly lower than for a starter

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sheet. In addition, permanent stainless steel cathode plate technology allows for shorter crop ages, which reduces the probability of slimes inclusion occurring.

The level of impurity associated with electrolyte occlusion has also improved noticeably. This is attributed to the improved cathode deposit smoothness achieved by MCM since introducing the thiourea reagent. MCM upgraded its electrolyte circulation system to ensure that all refining cells are now receiving the correct flowrate of electrolyte, and thus reagents are always available at the cathode deposit surface during electrolysis operations. The inherent flatness of a permanent stainless steel cathode plate and the shorter crop ages also contributes to the cathode deposit smoothness.

No change in the silver assay at MCM indicates that the level of silver codeposition is not influenced by the conversion to permanent cathode plates. MCM does not have sufficient quantities of bismuth, antimony and tellurium in its anode and electrolyte for the surface precipitation impurity mechanism to be noticeable.

Customer Acceptance
Figure 3 shows the percentage of copper cathode production that was suitable for direct despatch to customers as LME Grade A cathode. The long-term trend for starter-sheet production was 86.6%, with significant variability in conformance. This indicator has improved to 97.7% since the conversion of the refinery to the ISAPROCESS™, with a vast reduction in variability.Figure 4 shows a photograph of typical cathodes.

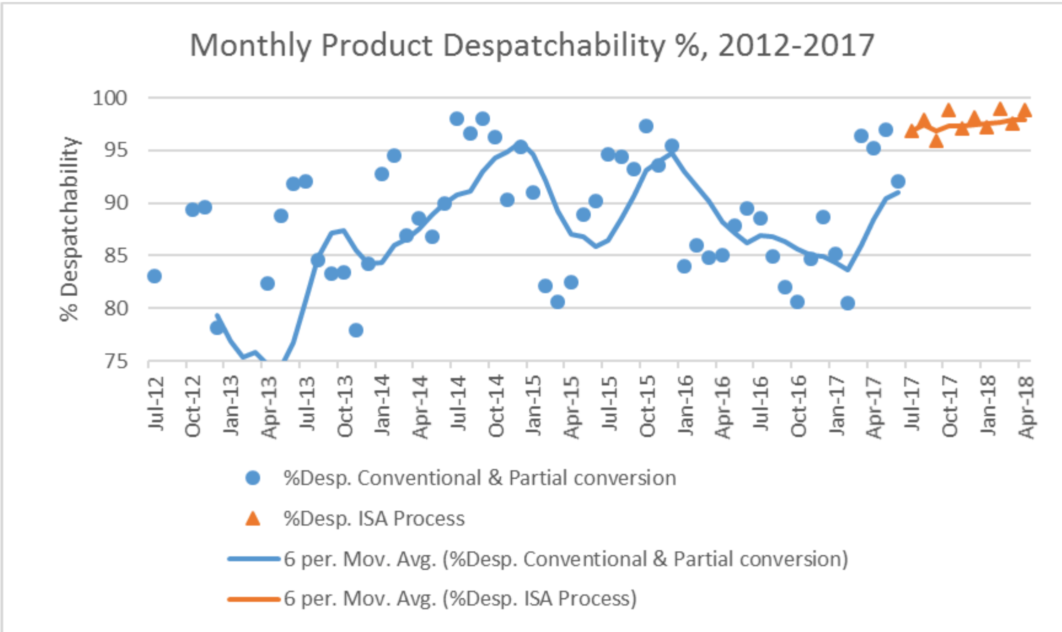

Figure 3. Cathode product dispatchability.

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Figure 4. Copper cathode at CSM and existing trolley system.

Current Efficiency

Figure 5 shows the long-term trend for refinery current efficiency (CE). The long-term trend for CE was 85.9%. This indicator has improved to 97.5% since the conversion to the ISAPROCESS™, due to significant reduction in the number of short circuits. The variability in month-to-month performance has also reduced significantly.

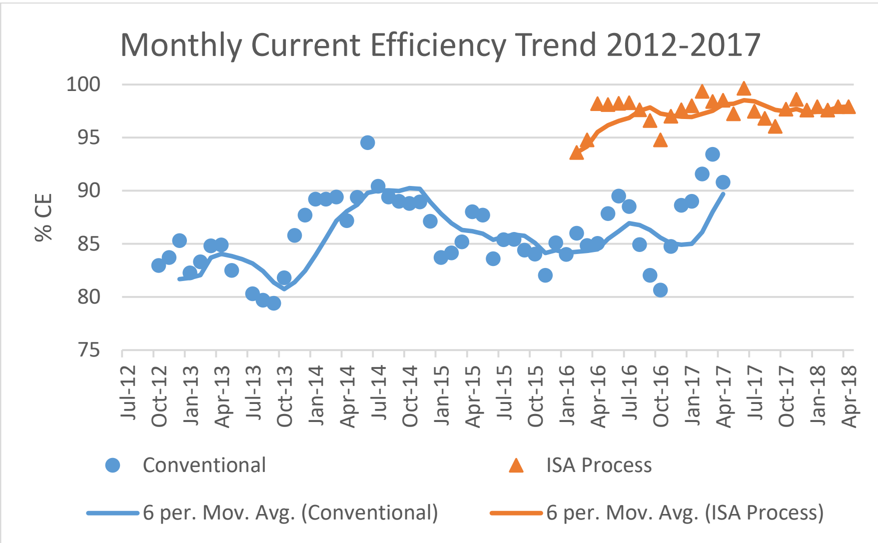

Figure 5. Current efficiency improvement after conversion.

Productivity

Figure 6 shows the long-term trend in labour productivity for the refinery. It is important to correlate this measure against the actual production level at the time. Refinery output was constrained significantly for two years between August 2015 and September 2017 due to the countrywide power shortages and MCM's business response to the crisis. Thus, to make a valid comparison, only months with production above 12 500 t are compared.

The long-term productivity trend for the starter-sheet refinery was 30 t cathode production per person-month. Since full conversion to the ISAPROCESS™, the productivity measure has averaged 41 t cathode production per person-month. This is a 37% improvement in labour productivity. As MCM returns to previous production levels, the productivity improvement achieved will continue to improve.

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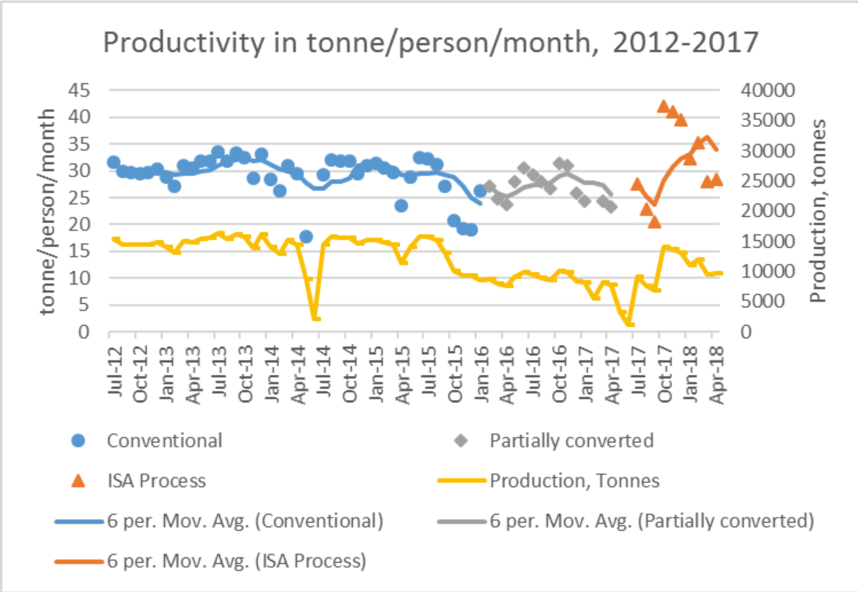

Figure 6. Productivity in tonne/person-month

REFERENCES

Aslin, N.J., Eriksson, O., Heferen, G.J., Sue Yek, G. (2010). Developments in cathode stripping machines- an integrated approach for improved efficiency. *Proceedings Copper 2010 International Conference, Volume IV Electrowinning and –refining*, GDMB. Germany. pp. 1253–1270.

Barrios, P., Alonso, A., Ortiz, C. (1999). Improvements in the operating practices at the Atlantic Copper Refinery. *Proceedings Copper 99–Cobre 99 International Conference, Volume III – Electrorefining and Electrowinning of Copp*er, Dutrizac, J.E., Ji, J., Ramachandran, V. (eds.). The Minerals, Metals and Materials Society, Warrendale, PA. pp. 291–299.

Dobner, R., Schwill, M. (1995). Modernisation and extension of a conventional tank house. *Erzmetall.*, 48, Jahrgang, Nr. 4/95, S. 272-276.

Jenkins, C. (1962). Plant designing for electrolytic copper refining. *Australasian Engineer*, 105, 42–45.

Moats, M., Robinson, T.G., Davenport, W.G., Karcas, G., Demetrio, S. (2007). Electrolytic copper refining – 2007 world tankhouse operating data. *Proceedings Copper–Cobre 2007 International Conference, Volume V-Copper Electrorefining and Electrowinning*. Houlachi, G.E., Edwards, J.D., Robinson, T.G. (eds.). The Metallurgical Society of Canada, Toronto .pp. 195-201

O'Kane, J. (1997). ISAPROCESS – Benchmarking copper refining electrolysis. *Proceedings GDMB 33rd Metallurgical Seminar*, Lunen, Germany. pp 67-82

O'Rourke B.J. (1999). Tank house expansion and modernisation of Copper Refineries Limited. *Proceedings Copper 99–Cobre 99 International Conference, Volume III – Electrorefining and Electrowinning of Copper*, Dutrizac, J.E., Ji, J., Ramachandran, V. (eds.). The Minerals, Metals and Materials Society, Warrendale, PA. pp. 195–205.

Robinson, T.G. (2002). Electrolytic refining. *Extractive Metallurgy of Copper*, 4th edn. Davenport, W.G., King, M., Schlesinger, M., Biswas, A.K. Elsevier Science, Oxford. pp. 265–288.

Wenzl, C., Filzwieser, A., Antrekowitsch, H. (2007). Review of anode casting – Part I: Chemical anode quality. *Erzmetall.*, 60 (2), 77–83.

MOUNT ISA MINES NECESSITY DRIVING INNOVATION

*V. Lawson, H. DeWaal, G. Heferen, N. Aslin, P. Voigt, and M. Hourn

Glencore Technology
Level 10, 160 Ann St
Brisbane, Australia, 4000
*(*Corresponding author: virginia.lawson@glencore.com.au)*

ABSTRACT

Mount Isa Mines (MIM) acquired a reputation for the successful application of R&D to develop break-through technologies for the mining industry starting in the 1978's through until the early 2000's. The ISAPROCESS™ tank-house technology has been licensed to copper refineries throughout the world, and a significant per cent of the world's copper is refined using this technology. Since development in the late 1980's more than 20 ISASMELT™ copper and lead smelting furnaces are now installed in countries around the world. Jameson Cell flotation technology developed jointly by Mount Isa Mines and Professor Graeme Jameson is widely used in the Australian coal mining industry and increasingly in the base-metal and gold industry. The IsaMill™'s developed at Mount Isa and McArthur River made it possible to develop the McArthur River and George Fisher orebodies and has been successfully implemented into base metal fine grinding applications around the world. The most recent commercialised innovation is the atmospheric leach Albion Process™ with its supersonic HyperSparge™ gas sparger, is being adopted as a solution to the increasing complexity of orebodies.

MIM's contribution to the industry was significant given the size and the remote location of its operations with Townsville Copper Refineries more than 1350 km and Mount Isa 1800 km from the nearest state capital of Brisbane. This paper will briefly discuss the development of each of these technologies and why MIM – now owned by Glencore - was so successful innovating and developing such technologies over a period of nearly 40 years.

KEYWORDS

Innovation, Mount Isa Mines, ISAPROCESS™, IsaKidd™, ISASMELT™, IsaMill™, Jameson cell, Albion Process™, HyperSparge™, ZipaTank™

INTRODUCTION

Mount Isa is located in the Gulf Country region of Queensland about 1800 kilometers North West of Brisbane (see Figure 1). It came into existence because of the world class mineral deposits found in the area. In 1923 the orebody containing lead, zinc and silver was discovered by the miner John Campbell Miles. Mount Isa Mines Limited (MIM) was founded in 1924 to develop the minerals discovered by Miles, but production did not begin until May 1931. It paid its first dividend in 1947 after 16 years of troubled production. In 1954 the 1100 copper orebody was discovered and with rapidly rising reserves during the 1950's and 1960's led to the construction of new concentrators to treat lead/zinc/silver ores in 1966 (#2 concentrator) and copper ore's in 1973 (#4 concentrator). The difficult nature of the Mount Isa lead-zinc orebodies has meant that the company had always needed to be at the forefront of mining technology. In the 1970's through to the 1990's, it became a world leader in developing new mining techniques and processing technologies as a response to declining metal prices and rising costs. Mount Isa has been smelting copper since 1953 and lead since the early 1930's. Copper Refining at Mount Isa's fully owned subsidiary of Copper Refineries Proprietary Limited (CRL) had commenced operations in 1959.

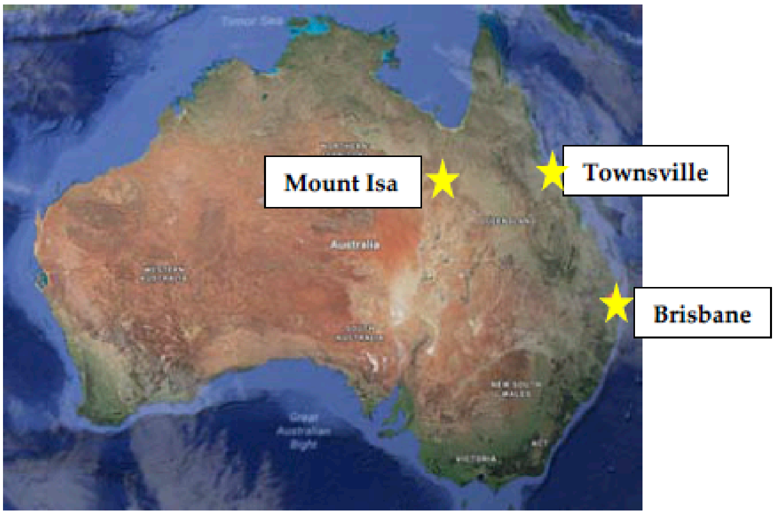

Figure 1 – Location of Mount Isa and Townsville relative to Brisbane the nearest Capital City

Technologies to come out of Mount Isa include the ISAPROCESS™ copper refining technology, the ISASMELT™, The Jameson Cell, the IsaMill™, the Albion Process™ and the Hypersparge™. Mount Isa Mines Ltd was acquired by Xstrata in 2003 and Xstrata was then merged with Glencore in 2015. The level of innovation achieved at Mount Isa Mines is unsurpassed and was the result of the difficult nature of the Mount Isa ore bodies and its response to declining metal prices and rising operational costs in the 1970's and 1980's. By the 1990's, Mount Isa had become a world leader in innovative mining techniques and state of the art processing technologies. The processing technologies are discussed below.

INNOVATIONS

Each of the innovations developed at Mount Isa Mines had a driver but the overarching desire was to make technology more efficient and cost effective. Each of these process developments will be discussed separately.

ISAPROCESS™

The development of the ISAPROCESS™ tank house technology had its beginning in the zinc industry. During the mid-1970s, MIM was considering building a zinc refinery in Townsville to treat the zinc concentrate produced by its Mount Isa operations. As a result, MIM staff visited the zinc smelters using the best-practice technology and found that modern electrolytic zinc smelters had adopted permanent cathode plate and mechanised stripping technology. MIM realised that the copper refineries performance was constrained by the conventional practice of copper starter sheets. The preparation of these copper starter sheets was labour intensive and the overall cycle was several weeks in duration.

MIM initiated a research program aimed at developing similar permanent cathode technology for copper refining. CRL, a subsidiary of MIM, had been operating in Townsville since 1959, using conventional starter-sheet technology and treating blister copper produced in the copper smelter at Mount Isa. Permanent cathode technology was developed and adapted over many years of in-plant experimental work and successfully introduced to the Townsville refinery in 1978. . The fundamental difference between the new ISAPROCESS™ and the conventional starter sheet technology is the use of a permanent reusable cathode blank instead of a non-reuseable copper starter sheet and the introduction of mechanised and automated electrode handling machines replacing labour-intensive manual operations. The vertical edges had plastic strips and the bottom cased in wax to prevent copper cathode from growing around the edges of the cathode plate during, stripping and allowing two separate copper sheets from each cathode plate. This technology led to major advances in the electrode handling systems and automation in copper tank houses. The improved geometry of the cathode plates and the significantly shorter cathode cycle times allowed for increased intensity and efficiency of the refining process. Introduction of permanent cathode technology resulted in higher capacity, better copper cathode quality with less defects, safer operation and a four-fold improvement in productivity. Considerable development work was required to modify the original stripping machines from their zinc cathode origins due to the heavier cathodes. The stripping capacity of the machines has increased from 250 plates per hour to 600 plates per hour in the latest designs. More recent developments include the elimination of wax masking from the cathode plate, robotic electrode handling machines, and the introduction Duplex Stainless Steel cathode plates giving greater durability and corrosion resistance. Through the use of ISAPROCESS™ user forums, to exchange ideas and developments in the technology and to share operational experiences, the technology has enjoyed continued improvement with higher productivity and improved quality at low cost.

Figure 2 – The IsaKidd process

In mid 1981 Falconbridge Limited commissioned a copper smelter near Timmins to treat concentrate from its Kidd Mine. The original copper cathode produced at Kidd suffered from the presence of higher concentrations of lead and selenium and could not meet customer specifications. It was determined that the use of copper starter sheets was preventing the Kidd refinery from meeting its cathode quality targets. Testwork began with the use of permanent stainless steel cathodes after preliminary tests showed a significant reduction in deleterious elements. The Kidd Process cathode used a solid copper header bar welded onto stainless steel resulting in a lower voltage drop than the ISAPROCESS™. Falconbridge began marketing the Kidd Process technology in 1992 providing competition between the two suppliers of permanent cathode technology. Between 1992 and 2006, 25 Kidd technology licenses were sold and 52 ISAPROCESS™ licenses.

The development of the ISAPROCESS™ and Kidd Process set the scene for a run of technology developments that continued until the mid 2000's. Xstrata took over MIM in 2003 and then Falconbridge in 2006. The Kidd Process technology consequently became part of the tank house package and together they have since been marketed as IsaKidd™ representing the dual heritage of the technology. The current robotic stripping machine (Figure 2) is based on over 30 years of copper refining and winning technology. Today over 100 licensees are using IsaKidd™ technology.

ISASMELT™

The sinter plant/blast furnace combination was the dominant technology for lead smelting throughout the 20th century. In the early 1970's companies using this technology came under sustained political and economic pressure as tighter environmental regulations were introduced, and energy costs increased, leading to higher capital and operating costs (Fewings 1988). It was in this environment that Mount Isa Mines sought a process that would improve the performance of the operations at their lead smelter in Mount Isa. After investigating the various processes under development, researchers turned their attention to the Sirosmelt lance. It had recently been developed on a laboratory scale at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Melbourne. Following initial investigations Mount Isa Mines recognised the potential of the novel concept for smelting of lead concentrates and embarked on an extensive development program.

In 1978 a joint project was initiated between Mount Isa Mines and CSIRO to investigate the application of the Sirosmelt submerged-combustion technology to the smelting of Mount Isa lead concentrates. The ISASMELT™ process, as it became known, was developed to maturity for smelting copper, nickel, lead and zinc feeds by Mount Isa Mines through the 1980's and 1990's using incremental scale up. Commercialization only occurred once the process had been proven on laboratory, pilot and demonstration scale over many years. Approximately ten years were required for development of the lead and copper ISASMELT™ from crucible to demonstration scale (refer to Figure 4). During this decade the core know-how that was accumulated enabled the development team to reach the point where they were much better equipped to design and construct a full scale commercial plant – the final stage of the scale up process. Key aspects in this process were the selection of the scale up factors and the systematic design, development and re-engineering of several components of the technology. Figure 3 shows a comparison for the scale up stages for the lead and copper ISASMELT™ processes. Pilot scale was defined as unity for scale up comparison.

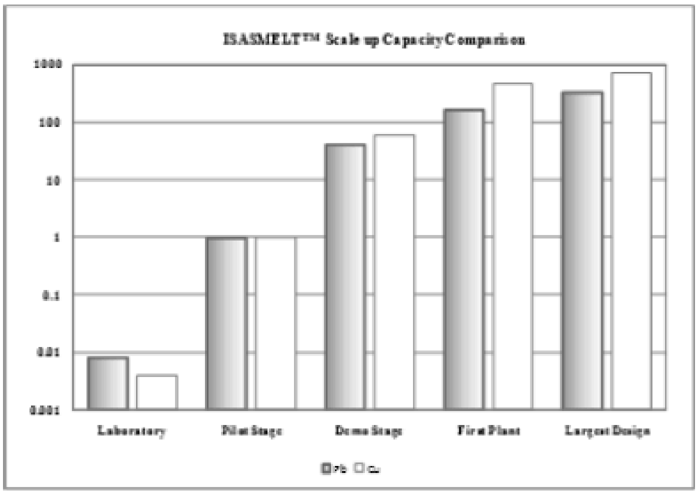

Figure 3 – Lead and copper ISASMELT™ Scale up comparison

During the scale up process, refer to Table 1, several aspects of the technology were developed to a high standard that allowed the ISASMELT™ technology to become a commercial success. As a result, ISASMELT™ technology now operates successfully at numerous plants around the world. The methodical approach to development of the technology has allowed owners to modernise their existing operations or create new businesses with significantly reduced technical risk.

An important parameter in the evolution of the ISASMELT™ technology has been the refractory campaign life. Figure 5 shows the history of the refractory campaigns at the commercial copper ISASMELT™ plant at Mount Isa since commissioning. At the time Mount Isa Mines management considered the installation of water cooling on the furnace refractories undesirable because of the potential for fatal incidents and increased operating costs. As a result the commercial scale furnaces were constructed with minimal water cooling. Although this led to shorter campaign lives initially, a development program was begun that focussed on optimising refractory materials selection and installation methodology. When coupled with process control strategies and continuous on-line monitoring of the bath temperature using systems developed over more than 10 years of operation, it allowed Mount Isa Mines to achieve campaign lives of more than 3 years without using any water cooling of the furnace refractories.


Figure 4 – Tapping matte from the copper ISASMELT at Kazzinc

Table 1 – Key Indicators of ISASMELT™ Plants from pilot to commercial scale

Topic	Unit	Pilot Scale		Demo Scale		First Full Scale		Current Design[1]	
		Pb	Cu	Pb	Cu	Pb[3]	Cu	Pb	Cu
Furnace ID	m	0.4	0.4	1.8	2.3	2.5	3.75	3.6	4.4
Lance Diameter	mm	38	38	150	250	250	350	250	500
Lance Control	-	Manual		Semi Automatic		Semi Automatic		Automatic	
Oxygen Enrichment	%	21	21	21	28	35	45	70	90
Nominal Feed Rate	tph	0.12	0.25	5	15	20	101	40	183
Offgas Treatment	-	Flue System / Baghouse		Gas cooler/ Baghouse		WHB		WHB[2]	

Notes:
ID: Internal Diameter; WHB: Waste Heat Boiler
[1] Refers to maximum throughput
[2] Some of the plants use a combination of radiation section and evaporative cooler for offgas treatment
[3] Refers to the smelting furnace from the two stage lead ISASMELT™ process

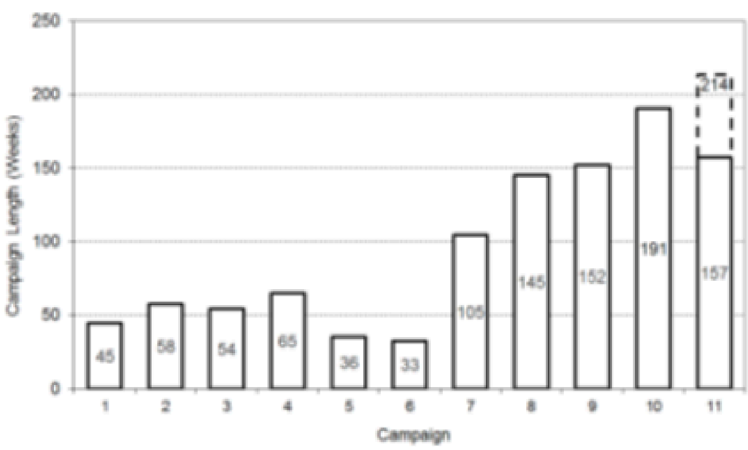

Figure 5 – Mount Isa copper ISASMELT™ plant campaigns (as of 2013)

Jameson Cell

The Jameson Cell (Figure 6) was jointly developed by Mount Isa Mines and Laureate Professor Graeme J Jameson (AO) of the University of Newcastle. Mt Isa had commenced operations with conventional flotation cells but was installing columns in cleaning duties in the mid 1980's. The columns had the benefit of froth washing that was likely to allow significant grade benefits in the very fine lead-zinc circuit. The first observations of the columns was that the collection process was slow necessitating long residence times and large volumes which remains a limitation of columns even today. In 1985 Professor Jameson was commissioned to undertake a project to improve the column sparger design.

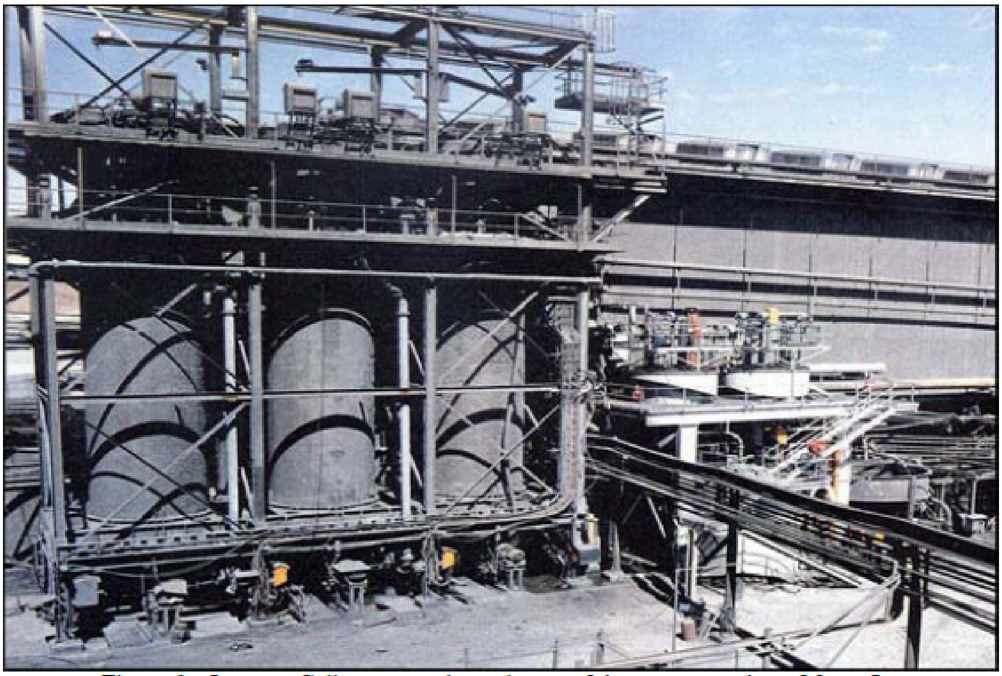

Figure 6 – Jameson Cells compared to columns of the same capacity at Mount Isa

Following initial work to provide an alternate method to bring together bubbles and particles, the downcomer was created. In the downcomer the air and the slurry are co-current with the air being entrained into the plunging jet under vacuum. Investigation showed that all of the bubble particle contact took place in the downcomer and thus the flotation tank could be much smaller. The first application at an industrial scale was in the lead zinc concentrator on the heavy media plant (HMP) lead slimes circuit. The initial improvement in performance were attributed to the very short residence time that allowed the minimisation of oxidation of galena fines. The cells were significantly smaller than the columns and there is no doubt the performance was superior as shown in Figure 3.

The testwork and trials in the early applications showed improved metallurgical performance when operated correctly. The challenge was operating them correctly. The technology hadn't been sufficiently developed to be successfully adopted into plant operations. The cell fell out of favour in base metals and in the 1990's was adopted into the Australia Coal industry and into niche SXEW applications where the main design challenges were resolved. The operability was improved by the introduction of a partial recycle to maintain constant flow and the maintainability of the cell was improved through various design modifications in operating plants. It was a period of continuous improvement. The result was a robust, low maintenance, easy to operate cell with the original features of excellent bubble particle contact.

The final obstacle was overcome when its adaption into the flowsheet was recognised to enable successful installations at the head of cleaner circuits and as low cost brownfield expansions. It is clear that the fast failures have had a significant effect on the success of the cell limiting its adoption into the industry. It is interesting that a significant proportion of sales are to return customers. Once you get over the hurdle of getting a Jameson Cell into your plant then seeing is believing. 2016 was the best year for Jameson cells into base metals and include the first sales back into South America where the cell had been abandoned after the difficulties of operations and maintenance of the Alumbrera installation. The metallurgical performance in Alumbrera was never the issue but the operators and maintainers hated the cells and they failed fast and hard.

The Jameson Cell celebrates its 30th birthday this year and has finally been adopted into mainstream base metals concentrators mainly as cleaner scalper at the head of the cleaner circuit. The cells generally recover up to 80% of the cleaner feed at high grades enabling much lower capital expenditure on the entire circuit. Process performance can be predicted from laboratory and pilot plant testing with demonstrated direct scale-up. It may have taken 30 years but the Jameson Cell is finally a success story. There are many lessons that can be learned from the implementation of innovation into industry from this case study.

IsaMill™

Unlike the developments of some of the other technologies at Mount Isa where efficiency was the main driver, the IsaMill was developed based on necessity. Figure 7 shows photomicrographs with the same scale of 40 micron demonstrating the increased complexity of Mount Isa ore over Broken Hill ore and the very difficult McArthur River ore. Although McArthur River was discovered in 1955 it was not able to be economically processed until the successful development of ultrafine grinding. McArthur River processing began in 1995 – 40 years after discovery when the IsaMill™ made it technically and economically feasible to grind all of the rougher concentrate to 7 micron to facilitate the rejection of non-sulphide gangue. Even at 7 micron galena liberation is not possible and a bulk zinc-lead concentrate is produced.

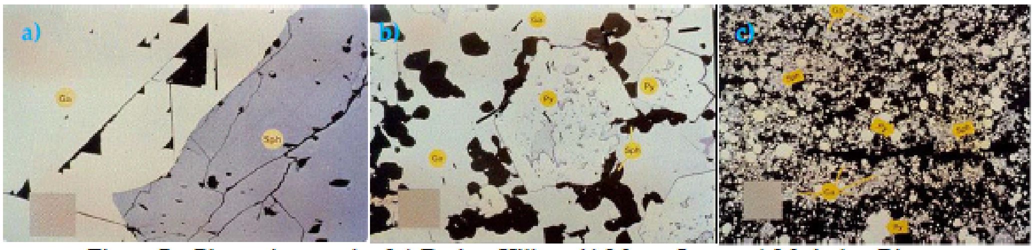

Figure 7 – Photomicrograph of a) Broken Hill ore b) Mount Isa ore c) McArthur River ore

Investigations into fine-grinding started at Mount Isa started in the 1970s using conventional grinding technology to increase mineral liberation by grinding to fine sizes. These technologies were not only found to have high power consumption but also proved to be detrimental to flotation performance as a result of pulp chemistry and iron contamination from steel media. These poor results were revisited during pilot plant and tower mill testwork in the 1980s which also showed an inability of tower mills to economically achieve the required sizes. When it became clear that the solution to efficient fine-grinding did not exist in the minerals industry, MIM looked for ideas to "crossover" from other industries that also ground fine particles – pigments, pharmaceuticals, foodstuffs (e.g. chocolate). While these mills operated at a much lower scale and treated high value products they demonstrated the principle that stirring fine media at high speed was highly efficient. The challenge was transferring this concept to continuous, high tonnage and lower-value streams in the minerals industry.

In 1991 the introduction of a Netzsch laboratory stirred mill to the Mount Isa site was a turning point in fine-grinding and ultrafine grinding. The ½ litre bench scale mill resembled a milk shake maker and used fine copper smelter slag as grinding media. Testwork on McArthur River ore started in 1991, and by January 1992, a small pilot scale mill, LME100, had been designed and installed at the Mount Isa pilot plant. The testwork showed that high speed, inert, horizontal mills could efficiently grind to 7 microns at laboratory scale providing major improvements in metallurgical performance. To make ultrafine grinding applicable to full-scale production a program of development was undertaken between Mount Isa Mines Limited and NETZSCH-Feinmahltechnik GmbH.

After 7 years of development and testing of prototypes in the Mount Isa operations, the IsaMill™ evolved. It was large scale, continuous, and most importantly robust because it was developed by operators. The crucial breakthrough was the perfection of the internal product separator – this allowed the mill to use cheap natural media (sand, smelter slag, ore particles) and to operate in open circuit. These are significant advantages for operating cost and circuit simplicity. Scale-up was tested using trial installations at the Hilton and Mount Isa lead/zinc concentrators. By the end of 1994, the first full scale IsaMill™ (1.1MW) was installed in the Mount Isa concentrator. Improvements to the technology were continually made by the operators, maintainers and engineers working with the technology.

In 1998 the rights for commercialisation of the IsaMill™ where transferred from Mount Isa Mines Limited to MIM Process Technologies (now Glencore Technology) and under an exclusive agreement with Netzsch. In December 1998, the IsaMill™ technology was launched to the metalliferous industry as a cost effective means of grinding down to and below 10 microns. The IsaMill™ is now a mainstream fine grinding machine with over 130 installations around the world.

The Albion Process™

In the 1990's, MIM were studying options for the development of the large Frieda River/Nena project in PNG through its subsidiary Highlands Pacific. The Nena ores were not amenable to smelting, due to the elevated arsenic content, and several hydrometallurgical options were examined. Out of this work, MIM developed the Albion Process™, named after the suburb in Brisbane where MIM's development laboratory was located. The Albion Process™ is a combination of ultrafine grinding using Glencore Technology's IsaMill™, followed by oxidative leaching at atmospheric pressure in a series of reactors designed to achieve high oxygen mass transfer efficiency. The HyperSparge™ was also developed to deliver oxygen to the reactors efficiently.

Various small scale continuous pilot plant campaigns were conducted in 1994 and 1995. A larger pilot plant (120kg zinc cathode/day) was constructed in 1997 to conduct testwork as part of a feasibility study on the zinc/gold resources of Pueblo Viejo in the Dominican Republic. Extensive piloting was also conducted on lower grade chalcopyrite concentrates for Cyprus Amax in 1998, and for Mount Isa Mines in 2000. Pre-feasibility and feasibility pilot testing was conducted on the zinc/lead bulk concentrates from McArthur River and Mount Isa in Australia between 2001 and 2005. During this time the Albion Process™ was successfully tested on over 70 different ores and concentrates. The process is designed to recover gold and base metals from refractory ores. The key to the process is the ultrafine grinding stage followed by a hot oxidative leach at atmospheric pressure.

In the period from 1994 until 2004, the Albion Process™ (see Figure 8) was seen as strategic to the MIM/Xstrata group, and was not marketed externally. In 2005, a decision was made to offer the technology to external clients under licence, and a marketing agent – Core Resources, was appointed to market the technology globally. Interest in the technology has been very strong in the subsequent period, with early licences signed in 2005 for the Las Lagunas Project, and 2006 for the Certej Project. The technology moved into commercial production in 2010 with the commissioning of Glencore's Albion Process™ plant in Spain (4,000 tpa zinc metal), followed in 2011 by the commissioning by Glencore of a second plant in Germany (16,000 tpa zinc metal). The Las Lagunas refractory gold project commissioned in 2012, and the GPM Gold refractory gold project commissioned in 2013.

Figure 8 – The Albion Process oxidative leach plant in Armenia

The major scale up risk with any oxidative leaching technology is oxygen mass transfer. High agitator power demands are common to achieve the shear rates in the vessel required for effective mass transfer at a commercial scale. A different approach was taken in the design of the Albion Leach Reactor to lower the agitator power demand. Glencore developed the HyperSparge supersonic gas injection lance to provide gas injection velocities of the order of 500 $m.s^{-1}$ within the leaching vessel, compared to the 4 – 8 $m.s^{-1}$ achieved with a typical agitator. Supersonic oxygen injection is a far more efficient method of generating shear than conventional agitation, allowing the total power input into the vessel to be significantly reduced, and greatly reducing the scale up risk for the oxidative leach.

The Albion Process™ was enabled by the fine grinding of the IsaMill™ and the process was designed to deliver a lower cost processing option for treating refractory mineral resources. There are now six operating Albion Process™ plants and the process has now an extensive database of potential applications.

CONCLUSIONS

MIM developed a significant number of processing innovations that are technical and economic successes. The ability to innovate at MIM was enabled by very challenging orebodies and the need to process efficiently to remain economically viable. The success has been attributed to the development of these technologies on an operating site with the R&D group solving the technical issues on small scale. Each subsequent scale up was completed in the operating plants where the operators, maintainers, engineers and metallurgists were required to achieve production goals at each step of the scale up to ensure funding for the next step.

The number of innovations, at MIM, was disproportionate to the scale of operations and may have been enabled by the remoteness of the site and the researchers and operators working collaboratively to solve economic and technical problems. The research group were not capital city based but worked on the same site and were required to assist with installation, commissioning and operation of the various stages. This co-operation led to adoption into the plant and a fast feedback loop for improvements. The ultimate success of the innovations has been their widespread adoption into the mainstream industry where feedback from operating sites based on a user group model has enabled continuous improvement of each of the technologies.

ACKNOWLEDGEMENTS

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technologies in their plants. The success of these developments continues with the input from end users in the ongoing development.

REFERENCES

Armstrong, W. "The Isa Process and its contribution to electrolytic copper," paper presented at the Rautomead Conference, Scotland, August 1999.

Fewings J.H., Management of Innovation – The IsaSmelt Process. Presented at AMIRA "Innovation in Metal Production" Technical Meeting at Mount Isa, October 3-4, 1988.

Fountain C. Isasmelt and IsaMills – Models of successful R&D – AusIMM Young Leaders conference, 19-21 March 2002, Kalgoorlie, W.A.

Nihill D.N., Stewart C M. and Bowen P. the McArthur River Mine – The First Years of Operation. The AusIMM '98 Mining Cycle. Mount Isa 19-23 April 1998.

Pease, Joe (August 2005), "Complex leaching becomes much simpler" (PDF), Australian Mining, pp. 26–32, archived from the original (PDF) on 12 September 2009, retrieved 6 January 2010

Pease, Joe September 2016, "Crossing the innovation valley of death" Presented to JKMRC.

Current distribution in modern copper refining

N.J. Aslin
Xstrata Technology
Hunter St
Stuart,QLD, Australia

D. Stone
PI International
3094 Emery Circle
Austell, GA 30168 USA

W. Webb
Xstrata Technology
Hunter St
Stuart,QLD, Australia

ABSTRACT

In today's modern copper electro-refineries, increasingly higher average current densities are being employed. With these increases many refineries are approaching their limiting current density. The nearness of the average operating current density to the limiting current density has placed increasing emphasis on the need to maintain an even current distribution. This paper explores the importance of maintaining even current density and discusses the factors, processes and practices that are necessary to achieve and maintain high quality production at high operational intensity.

INTRODUCTION

The copper industry was based essentially on the use of a copper starter sheet as the substrate for the refined copper deposition. In the 1970's operating current densities with this technology were typically around 220-250 amps per square metre.

There was a clear recognition that the maintenance of electrode spacing or geometry was crucial in minimising short circuits and rough growth within the cells. A number of systems aimed at rigidising the fragile copper starter sheets were introduced. These included a number of both pre and post-installation straightening systems including starter sheet embossing and restraightening systems such as the PD press.

The pursuit of the vertical electrode culminated in the introduction of permanent stainless steel technology by the ISA PROCESS™ group in 1979 at MIM's Townsville Refinery. The introduction of this inherently straight permanent cathode technology led to its combined use with high quality anode straightening machinery and crane placement systems. These combined systems led to very predictable electrode geometry and inter-electrode gaps, resulting in superior cathode quality at high current density.

The industry now had a refining system, which had overcome much of the labour intensive tasks associated with maintaining correct and even electrode spacing.

Limiting Current Density

A key industry target has been to increase productivity and reduce costs while improving product quality. Increasing current density has been an important element of this aim, along with larger electrodes, closer spacing, larger numbers of plates per cell and higher time efficiency.

The maximum current density possible is related to the ability of cupric ions to migrate to the cathode surface as quickly as those ions can discharge from the anode. This is driven by the diffusion rate of cupric ions across the boundary layer at the cathode face. The thickness of the boundary layer depends on many factors including flow rate of the bulk electrolyte and the concentration gradient across the boundary layer. This process is described by Fick's Law (1), which can be written as;

$$\frac{-dQ}{dT} = \frac{D(C_b - C_e)}{d} \quad (1)$$

where C_b is the concentration of the cation (cupric) in the bulk solution (mol/m^3), C_e is the concentration of the cation at the electrode surface, d is the distance over which the concentration change occurs (m), D is the diffusion coefficient (m^2/s). dQ/dT is the flux in mol/m^2/sec.

If the current density exceeds the ability of cupric ions to diffuse across the boundary layer the current will be carried by cations other than copper, and a reaction other than copper reduction at the cathode will occur. The limiting current density can be written as the equation;

$$i_{\text{lim}} = \frac{nFDC_b}{d} \quad (2)$$

where i is the current density (A/m^2), F is Faraday constant (C/mol) and n the number of moles of electrons in the electrochemical reaction.

This condition exists when the cupric ion concentration is zero at the electrode. If more current is driven through the electrode it will be carried by cations other than copper. In electrorefining, this would normally be Arsenic and possibly Bismuth or Antimony.

A key factor here is that the limiting current can be reached at any electrode, or part of an electrode in a cell, prior to the full set of electrodes reaching their limiting current. This results in the generation of a rough and open structure in the high current density regions. This cathode will not comply with the criteria specified by international standards. Rough growth in turn can result in the inclusion of slimes and electrolyte within the structure. Both occurrences will result in non-compliant product.

Quality Considerations

In a copper market where demand outstrips supply, the minimum standard is often sufficient. However in a less favourable market, only suppliers of the highest quality copper will maintain full sales of their product and achieve maximum premiums over standard product value. In the modern era, downstream fabricators are under constant pressure to reduce their costs. These companies are becoming less inclined to accept the need for rework due to poor raw material supply.

Table I – Cathode Quality Standards versus Typical ISA PROCESS™

Element	LME Limit ppm	ASTM B115 (COMEX) Limit ppm	Xstrata Refinery (12 month average) ppm
Pb	5	8	0.1
As	5	5	0.5
Sb	4	5	0.2
Bi	2	2	<0.1
Ag	25	25	12
S	15	25	5
Fe	10	12	<0.1
Ni(+other)	20	8	0.6
Se	2	4	<0.1
Te	2	2	<0.1

While the LME and Comex standards are recognised internationally as good supply, copper producers are now aware that simple compliance is not enough. Some of the world's key wire-rod producers will simply not accept sulphurs above 5 ppm. Lead concentrations should be maintained well below 3 ppm.

Current Distribution - Theory

Electrode pairs in a cell are arranged in parallel with the direction of current flow, such that total cell current divides between the electrode pairs in accordance with Ohms Law. The current passing through each electrode pair is inversely proportional to its component resistance.

Ideally, if all resistance paths are equal, the cell current will divide so that all the electrodes will operate at the mean current density over the entire surface of the cathode. In practice however, variations in ohmic resistance between electrode pairs leads to non-uniform current distribution. The range of current densities within each cell approximates a ‘normal’ distribution. Cathode plates at the extreme high end of the range are the first to exhibit rough growth and ultimately cause short circuits. These highs also restrict the ability to raise the mean current density because they impact on the current efficiency and cathode quality.

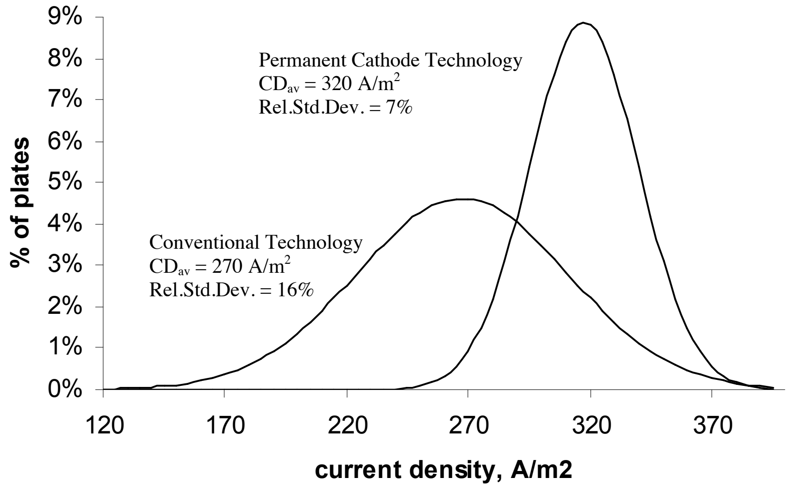


Figure 1 – Current Distribution Comparison - Conventional and Permanent Cathode

Factors affecting Current Distribution

The causes of non-uniform current distribution are simply those physical characteristics that affect the electrode pair resistance, namely;

- Electrode cell spacing
- Electrode alignment
- Electrode physical geometry
- Electrode contact resistance
- Electrode internal resistance

The factors that have greatest impact on current distribution will be those which contribute the greatest component voltage to the overall cell voltage.

Table II – Cell voltage Components, typical modern refinery*

	Components of Cell Voltage, mV		
	Crop 1	Crop 2	Crop 3
Anode contact voltage drop	10	10	15
Electrolyte voltage drop	220	270	320
Cathode plate internal resistance	25	25	25
Cathode plate contact	25	25	25
Anode overpotential	-340	-340	-340
Cathode overpotential	340	340	340
Total Cell Voltage	280	330	385

* permanent cathodes, 600 Amps/plate (300 A/m^2) electrode pitch 100mm

Electrolyte Resistance

Electrolyte resistance is by far the major component, representing 80-85% of total cell voltage. Therefore small changes electrode geometry that affect inter-electrode gap will have a major impact on the electrode pair resistance and current distribution. Electrode spacing and geometry are the key variables that must be controlled to optimise current distribution. This is particularly true in modern high-intensity refineries that use increasingly thicker anodes and closer electrode pitch. As anode thickness increases, the current distribution becomes increasingly sensitive to variations in inter-electrode gap.

Electrode Contact Resistance

In a modern refinery, the average cathode plate contact voltage accounts for 8-10% of the overall cell voltage. However contact voltage is often highly erratic, depending on the physical condition of the contact surfaces. Field measurements show that individual contact resistance typically ranges from 20-200 μO, equivalent to 5%-25% of total cell voltage. Cell contacts can therefore have a substantial effect on current distribution if not correctly managed.

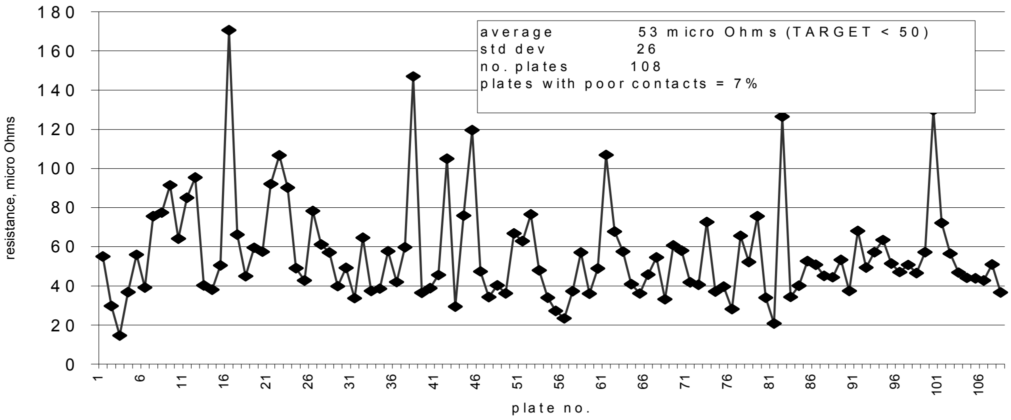


Figure 2 – Cathode Plate Contact Resistance

Electrode Internal Resistance

Cathode plate internal resistance depends upon the plate design characteristics. A typical ISA PROCESS™ plate accounts for around 8% of total cell voltage. However more important is the ability of the cathode plate to maintain low resistance over the duration of its life. Inferior plate designs result in a marked deterioration of electrical properties over time. Therefore plate internal resistance becomes a significant component in the overall cell voltage, and variable plate resistance will impact current distribution.

Anode resistance (both internal and contact resistance) is typically less than 2% of the cell voltage and therefore has negligible effect on current distribution.

OPTIMISATION OF CURRENT DISTRIBUTION

Electrode Alignment

Electrode geometry and alignment have long been recognised as the essential requirements for producing high quality cathode at high current density. With the use of increasingly narrow inter-electrode gaps, small deviations in electrode spacing have a proportionately larger impact on the inter-electrode gap and therefore on current distribution.

The aim of alignment is simple in theory. Anodes are placed at a fixed and uniform pitch in the cells, using the mould face of the anode lugs as a reference. Plates are then interleaved so that the blade is equal-distant from each adjacent anode face.

Alignment practice is carried out either automatically with advanced crane systems, or manually by the tankhouse operators. Both methods are capable of good results when implemented correctly. The main benefit of crane alignment is consistency and repeatability.

Manual alignment techniques commonly employed include the following;

Torching in – The gap between anode and cathode blades is checked visually with the aid of a hand-held light during the anode change, without electrolyte in the cell. This time-consuming method is most useful when anode physical quality is poor.
Visual Spacing – Anodes and cathodes are positioned in relation to reference points on the cell-top furniture (insulators and / or contact bars).
Spacer tools – A hand-held spacer bar is used to re-position the cathode hanger bars to a set distance from the mould face of the anode lugs (equal to the theoretical spacing for nominal anode thickness).

Some modern operations have the capability of automatically aligning the electrodes, such that little or no manual adjustment is necessary. This requires integration of the anode preparation machine, cathode stripping machine and overhead cranes, such that;

- ➢ The anode preparation machine and cathode stripping machine deliver electrodes to the crane at precisely the correct pitch. Anodes are positioned via the ‘mould’ side, which has less physical variance than the ‘set’ side.
- ➢ The crane is capable of maintaining the electrode pitch during loading / unloading and during transit. The crane hooks must positively locate the cathode plate hanger bars and have minimal free tolerance. Hooks must be robust enough to resist bending.
- ➢ Final placement (fine-positioning) of the crane bale on the cells must be highly accurate. Positioning devices used include laser targets and the more positive mechanical systems (cone or pyramid). ‘Stiff-leg’ cranes facilitate location of the bale onto the positioning device.

- The position of the cathode hooks relative to the anode hooks must be adjusted to the correct spacing, and checked by actual observation of the cathode. This action must be precise and repeatable.
- To enable the crane system to function as designed, the cells and cell-top furniture must be positioned accurately and remain fixed in place.

Xstrata's refinery in Townsville has operated two fully automatic cranes since it underwent a major refurbishment in 1998. These cranes are highly reliable and consistently place the electrodes within 2mm of their intended target. The alignment capability of the anode preparation / cathode stripping machine / overhead crane system is checked daily, by placing one set of electrodes in a calibrated portable rack.

Anode Quality

Variable anode geometry has a significant impact on inter-electrode gap and therefore current distribution. To fully realise the benefits of permanent cathode technology, significant improvements to anode quality were needed. Anode geometry had become a limiting factor in refining performance, which led to improved casting practice and better anode preparation.

There is now greater onus on casting operators to deliver anodes of consistent weight that are free from bowing, taper, fins or wash. A five percent variation in anode weight can result in blade thickness variation of 2-3mm. This is significant in high intensity refineries where inter-electrode gap may be less than 20mm on crop 1[1]. Modern weight-controlled casting systems are capable of delivering weight control within 2% of the target.

Key improvements to the anode preparation machines include lug contact milling, face milling and lug centring. More sophisticated machines also measure lug and blade thickness at various points in the press, and reject / accept anodes based on thickness, taper and other dimensional criteria.

Lug face milling and lug centring reduces interference between lugs that would otherwise prevent proper alignment, particularly in high-intensity cells with narrow gaps. These features also facilitate crane handling by ensuring the anode lugs are compatible with the crane hooks. Lug centring also aids manual alignment by allowing operators to more easily judge by eye the correct position of the lug. This can be difficult with off-set lugs.

A further contribution to improved alignment comes from the introduction of narrower cathode plate hanger bars, made possible by the high strength of the stainless steel hanger bars system. ISA PROCESS™ has supplied hanger bars to a width of 25mm in response to customer requirements. The strength of the stainless steel hanger bar

[1] Based on ISA PROCESS plant operating with 400kg anode and 95mm pitch

ensures the mechanical properties and geometry of the plates will not be compromised over time.

Operating Cycles

Permanent cathode technology offers greater flexibility with stripping schedules than can be achieved with conventional technology. Anode / cathode cycles can be varied to suit operational requirements. A practice commonly used in high intensity refining is to vary the anode / cathode cycle to optimise current distribution, including;

- Reducing the anode weight and cycle time, to increase average inter-electrode gap. Anode cycles from 14 to 21 days are used amongst ISA PROCESS™ operators. Example – 5d / 5d / 6d (crop 1 / crop 2 / crop 3)
- Shortening crop 1 duration and extending crop 3 duration, to maximise current efficiency (inter-electrode gap increases with crop number). Example – 6d / 7d / 8d
- Shortening crop 3 duration, to minimise poor current distribution arising from light anode scrap / poor anode contacts in latter crop 3. Example – 6d / 8d / 7d
- Converting to a 2 crop operation instead of the traditional 3 crop operation. This reduces anode weight and therefore inter-electrode gap. Example 7d / 7d. (Often two crops are used to achieve other objectives such as increased cathode weight, or reduced workload on the machines – Example 10d / 10d).

Electrode Geometry

The single most significant property of permanent cathode technology is the vastly improved plate geometry. This is particularly well demonstrated by the benchmark ISA PROCESS™ refineries around the world.

Performance of traditional refineries was constrained by the poor cathode geometry inherent with copper starter sheets. This was despite innovations such as embossing, rigidising and pressing of the starter sheets. Permanent cathode technology provided the step-change improvement in cathode geometry that was needed to make high intensity refining possible.

Cathode Plate Verticality

Verticality of the cathode plate is essential for achieving uniform current density over the face of the cathode plate. Non-vertical plates are subject to localised high current density in the bottom portion of the plate, leading to rough growth, increased entrapment of impurities, proximity shorting, and lowering of the effective limiting current density.

In modern refining with narrow inter-electrode gaps, small deviations in verticality can have significant impact on current distribution. A plate that is hanging 6mm off-plumb will raise the current density by a factor of 30% in the lower region of the plate[2]. As the intensity of refining increases, demands on plate verticality become greater.

Manufacturers of quality cathode plates should achieve verticality tolerance at least ± 5.5mm (centre-line deviation from vertical). Operators are demanding even stricter verticality tolerance in some operations.

While construction tolerances are important, the ability of the plate to maintain its geometry in service has a far greater impact on long-term plant performance. Plates must be robust enough to resist bending. The hanger bar system is a critical design feature that imparts overall strength to the plate, and provides rigidity to the blade. Hanger bar systems can be either copper or stainless steel. A copper-plated RHS stainless steel hanger bar, welded to a high chemical and physical quality stainless blade, has proven to produce the most consistent long-term performance.

Proper management of process parameters including electrolyte composition and reagent levels, will preserve the blade surface condition and maintain copper stripability. This in turn minimises mechanical damage during stripping.

Routine checking of plate verticality is also highly important. Non-vertical plates can generally be repaired on site using a simple peening technique.

Anode Verticality

Anode verticality is equally important as cathode verticality. Traditionally anode verticality was often achieved by inserting packing under the lugs to alter the hang of the anode, during torching-in.

Significant improvements were made with the introduction of pressing and contact milling in the anode preparation machines, as highlighted already. Lug pressing should incorporate re-setting of the lugs to the centre of the blade. Measurements have shown (2) that anodes with off-set lugs tend to hang 7-8mm off-plumb, and this can be overcome by centralising the lugs.

Contact milling improves verticality by providing a flat, regular contact surface. Correct maintenance and set up of the milling equipment and cutting heads is critical.

Cathode Plate Flatness

The inherent flatness of stainless steel cathode blades is a key factor in the success of permanent cathode technology. Today's manufacturers can supply to a flatness tolerance of 3mm. However, the on-going flatness of the plate is more important

[2] assuming 17mm inter-electrode gap, crop 1

than the original flatness tolerance. This is a function of blade thickness, hanger bar type and plant operating conditions.

A blade thickness of 3.25mm for most applications has proven to be the most cost-effective, in terms of current efficiency, plate maintenance costs and ultimate service life.

The hanger bar system provides much of the overall strength and rigidity to the overall plate assembly. Alternative hanger bar systems provide varying degrees of strength, however it is generally held true that stainless steel hanger bars provide optimum strength and durability. While solid copper hanger bars are widely used, a long-term bond between the copper bar and the stainless steel blade continues to elude manufacturers.

Plates that are bent or bowed may be tolerated provided they hang within an acceptance envelope (eg 14mm for a 3.25mm plate). The allowable envelope becomes tighter as current density increases or electrode pitch decreases. The decision to straighten a bowed plate should be based on hang-test results rather than absolute blade flatness.

On-going management of cathode plates is the key to their long term performance and extended life. Mechanical damage to the cathode plates can occur during crane handling, in the stripping machines, or through manual handling during repair and manual stripping. Areas that are often problematic include;

- Plates can collide with anodes or cell walls during cell loading, or strike feed conveyors during machine loading. Cranes should have accurate bale positioning, and incorporate sensors, which stop the bale from lowering when ‘plate-high’ is detected.
- Stripping machines must be engineered and set up to eliminate impact points. Automatic hammering of cathode plates to remove difficult-to-strip copper is not recommended by the ISA PROCESS™ as it can stretch and deform the plates.
- Incorrect manual stripping techniques have the potential to cause severe mechanical damage to the plate, which can affect its hanging geometry.

Cathode Plate Contact Resistance

Contact Maintenance

The contact resistance of individual cathode plates typically accounts for between 5% and 25% of the overall electrode pair resistance. The large variation is due to the high sensitivity of plate resistance to the condition of the contact surface.

Uniform contact voltages within a cell are far more important than the absolute value of contact voltages. Average contact voltage impacts power costs, while the variability determines current distribution. Uniform contact voltages are realised by having well maintained cathode plate hanger bar and intermediate busbar contacts.

The stripping machine washing system must incorporate contact cleaning for removal of organics, copper oxide and electrolyte salts. Modern machines have targeted contact cleaning systems using high-pressure hot water. Small quantities of sulphuric acid can be added to the wash water to aid removal of copper oxide and improve contact voltages.

Routine cleaning of the intermediate bars must also be undertaken. Contacts should be cleaned by scrubbing with dilute acid during anode changes, and by hosing during cathode harvests. More frequent wetting of the contact zones should be avoided because copper corrosion will result in variable contact voltages.

To avoid dripping electrolyte on contacts, the cranes can be fitted with drip trays. The trays should be fully engaged prior to travel.

Intermediate Bar Design

An important aspect of intermediate bar design their ease of cleaning. There should be no recesses or crevices that allow electrolyte to pool, or the resulting salts that accumulate will corrode cell-top furniture and hanger bars, leading to poor current distribution.

The conventional busbar system used is the Walker system (3), where electrode pairs within each cell are connected electrically in parallel. Intermediate bars between each cell allow equalization of current passing from one cell to the next. Intermediate bar contacts are generally of dog-bone or triangular profile, which provide a high-pressure point contact when used in conjunction with round-contact hanger bars.

Alternative designs have been developed that are aimed at overcoming the perceived shortfalls of the conventional busbars system.

Wet contact systems (developed Hibi Kyodo Smelting, Japan) was used for many years at Xstrata's refinery and gave clear benefits with regard to current distribution and power costs. However there was also a cost associated with increased corrosion of intermediate bars and hanger bar contacts, and high water inputs to the electrolyte (4).

Double contact systems have been promoted for improved current distribution. All like-electrodes (cathodes to cathodes and anodes to anodes) in each cell are connected via a secondary copper equalizer bar, providing an alternative electrical pathway between electrodes. This system has proven useful where the primary contact is compromised. While conceptually sound, there are issues relating to cleaning and maintaining currently offered systems.

Optibar have developed a Segmented Contact System (5), which is based on a similar principle to the original Whitehead system (6). Each cathode is electrically connected to an anode in the following cell, while each anode / cathode pair is insulated from the other electrodes (no intermediate distributor bar). It is claimed to improve current density dispersion, giving higher current efficiency, better cathode quality and less shorts.

Cathode Plate Internal Resistance

Internal plate resistance normally accounts for 8-10% of the overall cell voltage. The majority of cathode plate resistance occurs within the stainless steel 'free-board' zone between electrolyte solution line and the first copper plating. A much smaller resistance exists in the hanger bar itself.

The ISA PROCESS™ electroplated hanger bar design makes use of this property to significantly reduce overall plate resistance, so lowering power consumption. The copper coating extends from the hanger bar, across the welded joint and partially down the blade. This minimises the high resistance path across the stainless steel. The latest ISA Cathode BR™ plate extends the copper depth from 15mm to more than 50mm giving superior electrical performance.

Solid copper hanger bars incur much larger power losses through the high resistance path between solution line and hanger bar. This results in a significantly higher internal resistance than electro-plated designs.

Low internal resistance is important for minimising power consumption, however uniform current distribution requires uniform plate resistance from plate to plate within a cell. Therefore the electrical properties of the plates must be maintained over many years. The predominant cause of diminishing cathode plate electrical performance is the corrosion of the hanger bar to blade brazed joint that occurs in some plate designs. Since corrosion rates vary between plates, this results in variable current distribution within a cell, particularly when new plates are intermixed with older plates.

The electrical performance of electro-plated hanger bars is essentially unaffected by corrosion in refineries. This is evidenced by operations at Brixlegg, Olympic Dam and Copper Refineries, where plates have operated for 15 years to date without significant corrosion.

Measurement of Current Distribution

Routine measurement of current distribution and contact voltages should be undertaken. This provides a valuable measure of the capability of the overall system encompassing anode and cathode geometry, alignment accuracy and contact condition. Plate currents are measured by inserting a DC clamp meter through the lifting window closest to the contact. A scale-up factor is applied to individual measurements, to account for the portion of current not measured at the window (scale up factor equals rectifier current divided by the sum of all measured currents within in a cell).

Cathode plate contact voltages are measured using a millivolt meter, then resistance calculated by Ohm's Law. Resistance is independent of current density so provides a better performance measure than contact voltage.

The measured plate currents should approximate a normal curve, with standard deviation ideally less than 10% of the average plate current, excluding shorts or open-circuits. Average plate contact resistance should ideally be less than 50 micro Ohms.

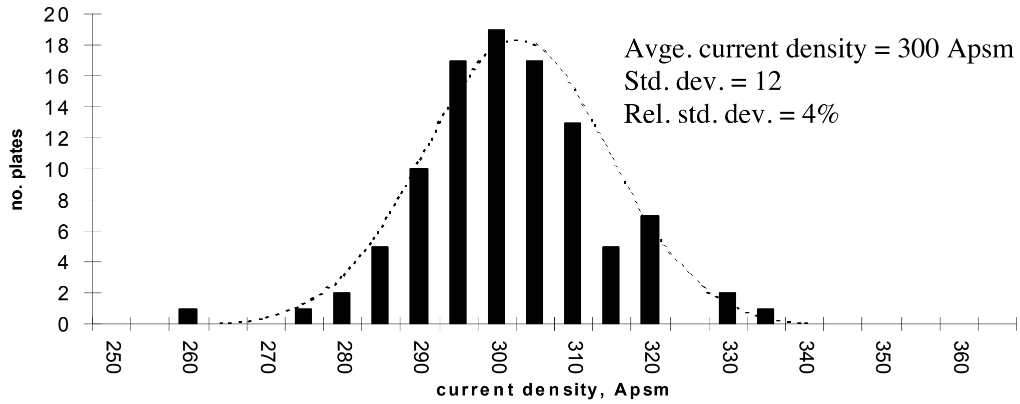


Figure 3 – Measured current distribution data, ISA PROCESS™ tankhouse (7)

Conclusion

The widespread introduction of the ISA PROCESS™ developed permanent stainless steel technology initiated a rapid increase in the intensity of the copper refining process. The superior and predictable verticality of permanent electrodes led to major improvements in current distribution and cathode quality, and increased intensity of operation.

Many refineries have benefited by achieving increased capacity of their plants at lower operating cost. The increased current densities being employed have required further improvements in the current distribution within cells and on cathode surfaces.

Improvements in anode preparation machinery and crane systems in conjunction with permanent stainless steel cathodes have further facilitated the improvement in electrode geometry. However the drive to reduce refining costs by increasing current density has caused greater emphasis on the ancillary components within the system. The need for a complete operating system with a key focus on the maintenance of current distribution is essential for production of high quality cathode demanded by the market place.

REFERENCES

1. J.O'M Bockris, D.M. Drazic, Electrochemical Science, Taylor and Francis Ltd, 1972

2. N.Kimlin, P.Hall, Anode Hanging Test, Internal Memorandum, Copper Refineries Pty Ltd, Box 5484 M.C, Townsville, QLD, Australia, Sept 2001

3. A.L Walker, Plant for the Electrodeposition of Metals, United States Patent No. 687,800, 3 December 1901

4. P.Hall, Dry Contact Trial, Internal Filenote, Copper Refineries Pty Ltd, Box 5484 M.C, Townsville, QLD, Australia, May 1994

5. G.A.Vidal, E.P.Wiechmann, A.J.Pagliero, Technological Improvement in Copper Electrometallurgy: Optibar Segmented Intercell Bars (Patent Pending), University of Concepcion, Faculty of Engineering, P.O.Box 160-C, Concepcion, 8 Region, Chile, Oct 2004, Canadian Metallurgical Quarterly, Vol 44, No.2

6. R.L Whitehead, Electrolytic Apparatus, United States Patent No. 1,206,965, 5 December 1916

7. N.Aslin, Commissioning Report, Copper Refineries Pty Ltd, Townsville, February 2003

Developments in Cathode Stripping Machines - An Integrated Approach for Improved Efficiency

N.J. Aslin, O. Eriksson, G.J. Heferen, G Sue Yek

Xstrata Technology
Hunter Street, Stuart
Townsville, Australia

Abstract

Copper cathode stripping machines and stainless steel cathode plates are critical elements determining the longevity, productivity and efficiency of modern tank houses. In the last decade notable innovations have been the ISA2000 and Kidd robotic cathode stripping machines, and enhanced integration with the overall electrode handling system. The acquisition of Falconbridge by Xstrata in 2005 provided a unique industry opportunity to bring two competing technologies together and has led to the development of a new stripping system which accesses the successful IP, experience and know-how of both ISA and KIDD systems of the past.

This paper presents a new copper cathode stripping system, developed and prototyped by Xstrata Technology in 2009, for the electro refining and electro winning industries. It features the use of robots for both the handling and stripping functions, providing a highly reliable, low-maintenance handling system. The flexibility that comes with robotic operation also offers shorter delivery time, simplified installation and high operational capacity.

The performance, safety and efficiency features of the new Xstrata Technology Robotic Cathode Stripping system are presented, along with an introduction to flow on impacts for other areas of tankhouse design and operation.

Introduction

The adoption of permanent stainless steel cathode electrodes in the electro-refining of copper was the most significant process development since the first commercial electro-refineries were built in the late 19th century. Invented and commercialised by Mount Isa Mines, the ISA PROCESS™ was first implemented into Copper Refineries Limited (CRL), Townsville, in the 1970's. The KIDD PROCESS by Falconbridge evolved in the 1980's and was first implemented into the Kidd Creek Tankhouse, both operations converting from traditional copper starter sheets.

Due to the permanent re-usable nature of the stainless steel cathodes, it has been a critical design requirement of electro-refineries to have an efficient and reliable integrated electrode handling and cathode stripping system. The acquisition of Falconbridge by Xstrata in 2005 has led to the development of a new cathode stripping system which accesses the successful IP, experience and know-how of both the ISA and KIDD systems.

Background

Permanent Cathode plate Technology

Numerous benchmarking studies [1,2] clearly demonstrate the widespread use and operational record of the ISAPROCESS™ and KIDD PROCESS for copper electrorefining and electrowinning. Today more than 11 million tonnes/annum of copper cathode is produced worldwide using ISAPROCESS™ and KIDD PROCESS. The significant features are summarised in terms of;

- Improved copper cathode quality
- Higher operating intensity and current efficiency, giving increased production rate per cell
- Longevity and Reliability
- Improved labour productivity
- Operational flexibility

Although stainless steel permanent cathode plates are critical components in maintaining a productive and efficient tankhouse, just as important are the stripping machines that process the Cathode plates on a daily basis.

Permanent Cathode Stripping Machines

The ISA and KIDD cathode stripping systems have both constantly improved and evolved as a result of the ongoing research and development carried out by MIM and Falconbridge respectively, resulting in several generations of CSM design over the past 30 years. The historical developments of the ISA and KIDD technologies have been well documented [3,4,5], and today there more than 100 installations worldwide.

The method of stripping copper from stainless steel and associated handling of the permanent cathode plates and the copper cathode product all have several options in their design and commercial application. Commercial applications can be grouped by the stripping mechanism, and material handling methods, as shown below in Table 1, summarizing the various stripping systems developed by Xstrata Technology.

Table 1 - Comparison of Layout, Materials Handling and Stripping Mechanism

	Low Capacity (<150 plates / hour)	**Medium-High Capacity (150–600 plates/ hour)**
ISA	➢ Flexor Stripper with Pivot Arm. ➢ ISA 2000 Flexor stripper	➢ Original ISA Machine, traverse conveyor, using wax bottom masking. ➢ ISA 2000
KIDD	➢ Standard Linear KIDD machine.	➢ Original KIDD carousel machine. ➢ KIDD multi-function stripping station using Robotic loading / unloading.

The key difference between the ISA and KIDD stripping mechanism is related to the physical form of the copper product. The ISAPROCESS™ stripping produces a split sheet product, 2 separate sheets of cathode from each Cathode plate, while the KIDD PROCESS stripping produces a V-sheet or "taco" style cathode copper which remains joined along the bottom edge.

Both types of copper product are widely accepted, and user preference often dictates design. For example, the ability to automatically reject only one side of the cathode plate using the ISA stripping system is preferred by many electrowinning operations, whereas the new KIDD stripping system is preferred by some refining operators.

Electrode Handling Systems

Efficient integrated electrode handling is paramount to a productively operating efficient tankhouse. The prime objective of the cathode stripping machine is to safely process the copper as quickly as possible, in order to minimise the downtime associated with cathode stripping operations. In business terms, asset utilisation and productivity comes through continuous plating of copper and this cannot occur unless blank SS Cathode plates are routinely returned to the electrolytic cells. Lost time efficiency from stripping operations generally accounts for around 4-6% in electrorefining operations.

The electrode handling system productivity depends on both mechanical and process factors. This section considers the main process related factors that affect overall cathode stripping machine throughput. Common causes of reject copper in the CSM are briefly given below;

- **Thin copper deposits** are caused by short circuits, limited plating time, poor alignment or poor electrical contacts. Thin copper is difficult to separate from the stainless steel plate due to its lack of rigidity, and generally requires rejecting and manual stripping
- **Sticky copper deposits** are generally related to poor surface condition on the cathode plate, such as corroded surface or improper mechanical treatment. These are also problematic to separate in the flexing station.

- **Heavily nodulated cathode** can often cause stoppages in the cathode stripping machine as the protruding nodules interfere with guides and other parts of the machine. It is generally more efficient to reject these plates than to attempt to strip them through the machine and risk long interruptions to the stripping.

- **Laminated Copper** is a particular issue that occurs with ISA 2000 cathode stripping machines. This results when DC power supply to the electrodes is stopped during the growth cycle, then resumed again, causing a lamination in the cathode deposit. While these events are rare, they can have a significant impact on cathode stripping rate for the affected cathodes.

  ISA 2000 stripping relies on the separation of the 'frangible' portion of copper inside the bottom edge v-groove, see Figure 1. This portion has a natural line of weakness starting from the void inside the v-notch and travelling downwards vertically through the deposit. Laminated cathode has a secondary line of weakness along the lamination which often affects the ease with which the two sheets can be separated. The ISA2000 cathode stripping machine successfully deals with this cathode by detecting splitting failure and automatically carrying out one or several repeat down-ending cycles (referred to as 'flapping'), however does lead to slower overall stripping rates as reported at the Hitachi refinery [6].

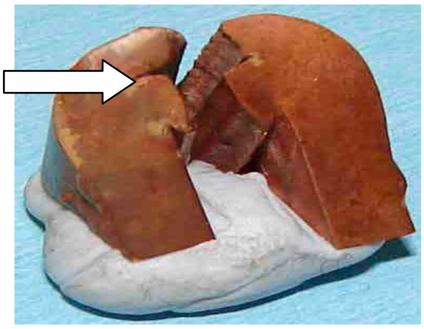


Figure 1 – Laminated Copper

Figure 2 – Magnified view of lamination

- **Strong Envelope c**aused by thick copper deposits or exceptionally hard copper. Causes curving above bottom of the cathode, difficult to separate, difficult to bundle neatly, aesthetics of final product lowered.

In summary, various operating factors can result in longer CSM cycle times, thereby lowering productivity and efficiency. Furthermore, manual handling by operators and other staff is generally required (increasing chances of injury) if separation can not be achieved. Therefore, it is apparent that a stripping machine needs to be designed to handle all types of copper deposit conditions as ideal conditions can not always be achieved in the real world.

Objectives and Methodology

The objective for Xstrata Technology in this development was to create a more accommodating and universal stripping machine, initially focussing on the production of spilt sheet cathode copper product. This new process was created with the goal of bringing the designed stripping rate, effective stripping rate and actual shift rate closer together. In order to achieve this, rather than designing to a specific and strict set of copper conditions, the new process and machine were designed to flex and strip copper regardless of how variable the deposit. Therefore, improving the reliability of the machine and meeting scheduled production rates independent of process variables.

The Xstrata Technology core designs principles were maintained, namely:

Safety - specifically the controlled handling of the copper cathode sheets during stripping operation, Reliability, Ease of Operation, Noise Reduction, Minimise potential for damage to the SS Cathode plates, Flexibility to handle all types of copper deposit and cathode plates, Maintainability and Sustainability across initial capital costs and investments to product and materials life cycle.

The design for the latest concept came as a result of a methodical and fresh approach adopted from the following:

1. Research and development conducted on several other successful Xstrata Technology designed, implemented and operating cathode stripping machines / processes.
2. Experience from numerous ISA/KIDD licensed refineries around the world.

Strengths and weakness from all machines were drawn upon when formulating the new Xstrata stripping concept. Standard design process and stages were then implemented.

Current CSM Technology

A number of machines were examined and tested in the creation of the latest robotic cathode stripping machine. A summary of operational backgrounds and key features from the existing designs that were critical to the development of the latest Xstrata Technology stripping system are presented below:

ISA 2000 CSM

The ISA 2000 Waxless machine uses hydraulics to drive a set of stripping knives downwards in between the copper cathode and stainless steel blade. This machine opens the copper envelope approximately 30 degrees each side (60 degrees total). The grippers then engage onto the copper sheets and the down enders rotate downwards about the bottom edge of the cathode until the copper sheets are taken just past horizontal position (approximately open to 195 degree angle). If separation does not occur, the downenders go up and down repeatedly (flapping) until the copper fatigues, cracks and separation occurs. The copper is then dropped onto a transfer conveyor where it is taken to be sampled, weighed, labelled, bundled and strapped.

The ISA 2000 CSM's have been operating successfully in refineries and electrowinning operations since 2001. They provide full control of copper sheets, produce a split sheet copper cathode product bundle and require minimal operator intervention during stripping.

Figure 3 – ISA 2000 Waxless machine stripping station

The need for improvement on this machine comes as a result of being originally designed to a strict set of "normal operating condition" copper deposits. Where there are variations in the operating conditions, the affects may result in increased cycle times. In addition, the force application position of the down ender grippers affects the separation reliability, especially when the copper is laminated or has a strong envelope.

ISA 2000 Flexor Stripper

This stripping system is a development based on the proven low capacity flexor stripper system patented by Xstrata Technology for use in electrowinning operations to allow operation without bottom edge strips or wax. The ISA 2000 Flexor Stripper uses a similar stripping function to that of the high capacity ISA 2000 Waxless machine.

The hydraulically driven knives on this machine extended the full width of the plate. This allowed the support and application of the stripping force across the full width of the stainless steel blade

and copper respectively. It also worked well in helping maintain a straight copper cathode in addition to aiding the separation of the cathode in the corners where it is generally more difficult to separate as shown in Figure 4and Figure 5 below.

Figure 4 – Thin Wedge, Curved copper due to separation issues on edges due to faulty edge strips

Figure 5 – Full Width Wedge, uniform copper separation

The first set of knives typically opened and split the copper. The secondary set of knives was used only when the bottom bond was strong or separation didn't initially occur (by opening the copper to the horizontal position). If separation still did not occur, flapping arms raised the copper back up to approximately 45 degree opening (90 degree open envelope) and then the knives were used again to bring it back down. Both sets of knives were attached to a “cassette” allowing the first set of knives to get closer to the bottom edge of the cathode (pivot axis of the copper envelope). The cassette moved up and down vertically and also had the flexing station attached.

This design allowed a full function machine to be compressed into the size of a single station making it ideal for space or capital limited operations, although cycle time is extended.

Critical learning’s during testwork included the difficulty in flapping using the two separate mechanical devices (knives and flapping arms) as they had to be well co-ordinated. It was also observed that very large forces were required to strip the copper due to the linear movements and no mechanical advantage or leverage in the mechanical devices. However, this was easily overcome through the use of hydraulics.

Successful implementation and operation of this stripping system has been applied at the Tenke Fungurume electro-winning operation, with several more systems due for commissioning in developing projects. It is best suited for low production applications.

Figure 6 – ISA 2000 Flexor Stripper

Roller Stripper

The Roller Stripper CSM was developed and commissioned on site at Townsville copper refineries in 2008. This machine was primarily designed for research and test purposes with some potential for retrofitting to existing ISA 2000 machines and greenfield installations.

The prototype machine employed a new concept in copper cathode stripping (patented by Xstrata Technology). The objectives of this design and development were to:

1. Reduce friction
2. Eliminate Plate damage
3. Maintain a flatter copper cathode

A three roller combination was formulated and uses similar motions to that of a normal wedge. The rollers extend the full length of the plate providing maximum support to the plate and stripping force to the copper. As shown in Figure 7 below, the top roller supports the plate and provides a reaction force to help separate the copper from the stainless steel blade. The middle roller supports and applies the stripping force to the copper cathode (this is normal to the roller and perpendicular to the face of the copper cathode). As the copper rotates towards horizontal, the force applied by roller 2 becomes vertical. The bottom roller is used when separation does not occur first time and provides support to the copper when bringing the rollers back up to the start position. The cycle is then repeated.

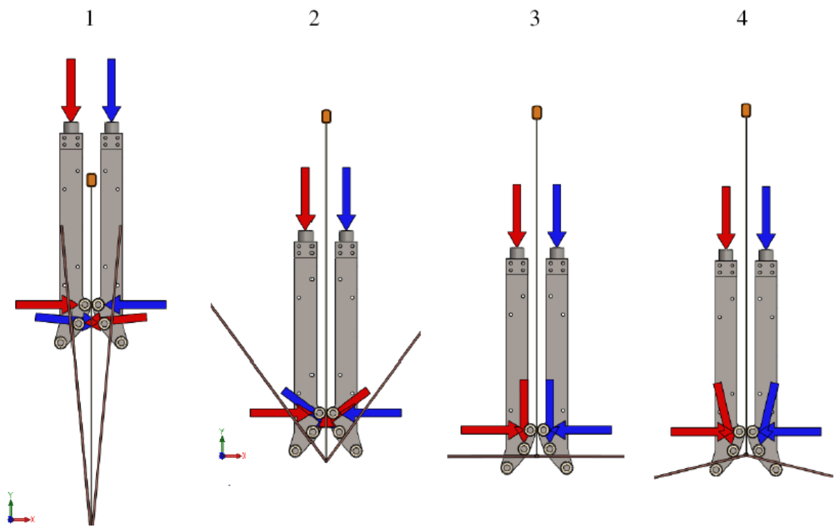


Figure 7 – ISA 2000 Roller Stripper

During testing it was observed that this machine was far superior in separating the copper sheets when compared to the previous two ISA 2000 machines. Test work demonstrated that in addition to supporting the copper across the full width, the rollers applied the force very close to the envelope pivot axis and concentrated all the fatiguing of the copper into the correct separation area.

This study gave an understanding of the critical force values which allowed the continuation and development of the new concept and confirming the possible use of robotics [7].

Other observations included:

- The ability to open the copper cathode past horizontal also aided in the fatiguing and crack propagation when trying to separate the copper. When the rollers moved upwards again, the force was still applied in the same position where as in other machines it can be dissipated and translates into bending of the copper cathode.
- The rollers were extremely quiet and left no plate damage.
- Maintains a very flat copper cathode sheet

The New Concept

It was apparent from the previous research and test work that the point of force application on the copper cathode had a substantial impact of the separation reliability. This was the main driving factor in the design and development of the new CSM process concept.

The following design parameters for the new concept were set based on the test work and operational experience from both the ISA and KIDD stripping systems:

- Small opening angle - Initially open the copper envelope as minimal as possible to prevent any bending of the copper in the sometimes weaker section just above the bottom edge of the envelope.
- Full width mechanism - Support the full width of plate (eliminate risk of plate damage) and copper (maintain straight flat copper cathode)
- Maintain or Increase Speed – Maximum speed to ensure fast cycle times
- Reliability – be able to strip the complete range of deposited copper from normal operating conditions to laminated
- Reduce Friction – to provide an efficient and lower maintenance machine

The following prototype was designed and constructed for initial testing on site at CRL. It comprised of four vertical members profiled in the shape of a wedge, it was designed to support the entire face of the copper cathode when rotating or stripping (Figure 8). The sharp angle allowed the wedge to reach the bottom whilst maintaining a minimal opening angle on the way down to prevent the copper bending as mentioned previously. The arms on either end locked in to a horizontal shaft to help keep the wedge in position during rotation, ensuring that the wedge made it to the bottom and guarantee that all forces were applied into the correct position on the copper cathode during separation.

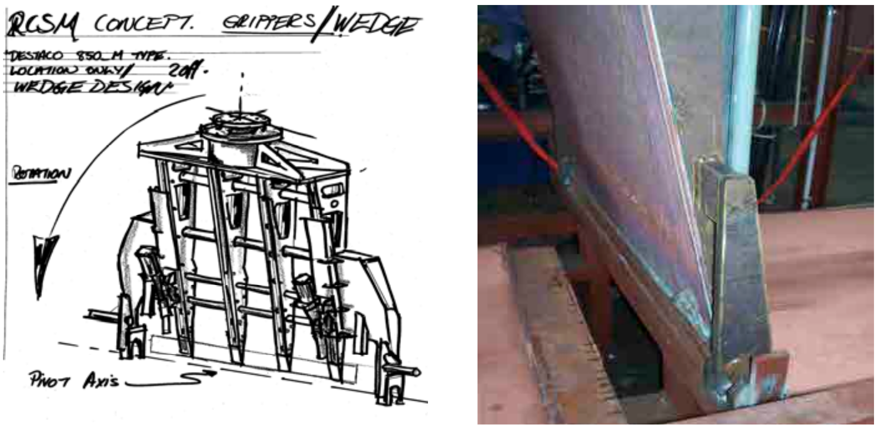


Figure 8 –Concept and prototype design

Some of the challenges in the design and development stages included:

- Forces involved with reaching the bottom

- Initial test results from the roller stripper and prototype wedge suggested that the forces required to get to the bottom of the cathode plate might have been above the capabilities of the available robots. After further testing and an investigation by John Hart, it was found that with the recent improvements and advancements in robots, they would be able to handle to task with slight modifications being made to the process and program of the robots to aid and ensure they would reach the desired point.

- Process difficulties (the range of movements required)
  - The new concept could be applied to either hydraulically driven mechanical components or robotics. However, due to the complex range of movements required by the concept process, it was thought that it was not practical, economical or desirable to construct using hydraulics.

The New Xstrata Technology Robotic CSM

Xstrata Technology has now taken the new concept through a complete design process and obtained a patent on the new cathode stripping process and design. Mechanical components driven by electrical devices, pneumatics or hydraulics could be used, however XT's determined that robotics was a far superior choice due to the many inherent advantages, namely:

- 80,000 hrs mean time between failure (MTBF) ~ 18 years at 12 hours per day
- High accuracy and precise movements - protect the SS cathode plate
- Proven capacities 900 kg and greater –capable of performing stripping function
- Flexibility – can be programmed and or easily changed to suit a wide variety of plates, copper conditions and equipment layouts
- Installation and commissioning time – very easy program modification and installation
- Excellent safety standards – program incorporated safety features + complete operator control with reduced or eliminated manual handling.
- Low noise and clean - no hydraulic fluids

The choice of robotics itself was innovative as this was the first time robotics were used in a copper tankhouse to perform a process or task other than simple pick and place materials handling.

Tooling Design

The design of the new robotic tooling (Stripping wedge) was the next critical stage and consisted of the following features:

1: Guides – implemented to support the copper during the downwards vertical motion, ensuring the copper does not pre-strip. In turn making the new process safer as there is complete control over the copper cathode at all times.

2: Grippers – used to clamp the copper before the rotational down ending starts, again, giving the robot and the tool complete control over the copper cathode at all times. In addition, this prevents slippage and concentrates all the forces on the void or weak spot in the bottom edge of the copper envelope.

3: Rollers – designed to reduce the friction between the copper, stainless and the wedge during the downwards vertical motion. This lowers the force required to get the wedge to the bottom whilst minimising or eliminating damage to the plate, wedge and copper. Finally, with the reduction of friction there is a reduction in noise and wear on respective components.

4: Wedge – the current prototype wedge was constructed from 350 grade mild steel and 316 grade stainless steel. Optimisation of materials of construction is ongoing.

   A. Wedge Frame – consisted of three vertical members for strength and rigidity whilst also providing attachment points for the guides, grippers and other equipment.

   B. Wedge Blade – featured a bevelled tip to ensure scratching or damage is kept to a minimum. This also allowed for maximum support of the copper cathode.

5: Pneumatic components – pneumatic components were used to maintain the goal of eliminating hydraulics. In order to reduce maintenance and maintain a cleaner work environment. Further testing is currently being performed to determine if the pneumatics can produce the required strength and forces needed to carry out the stripping process across all ranges of copper deposit and production hours.

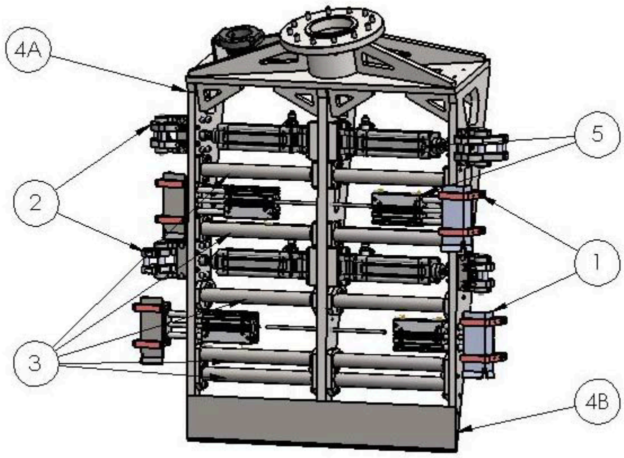


Figure 9 – ISA 2000 Stripping Wedge

Prototype Installation

On site at the Xstrata Townsville copper refinery a prototype robot cathode stripping machine was retrofitted into the original ISA 2000 waxless test stripping machine. As shown in Figure 10 and Figure 11 below, the robots greatly open up the stripping area allowing easy access for operators, maintenance, forklifts and other equipment.

Figure 10 – Before

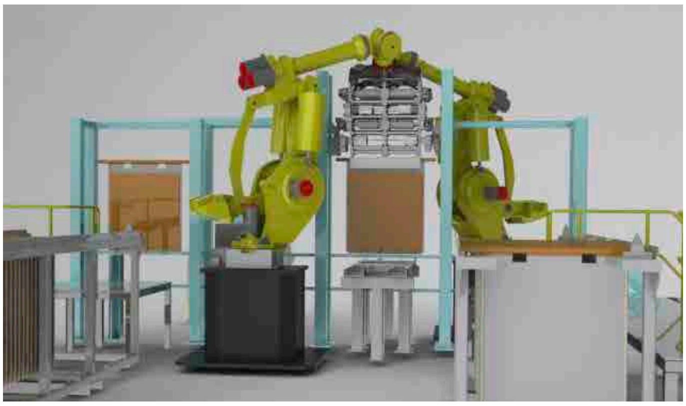


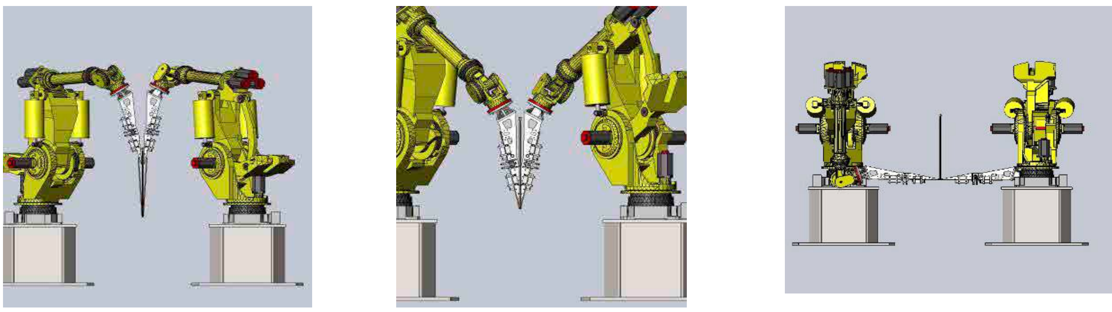
Figure 11 – After

Stripping Process

The process in which the wedge works is similar to the original ISA 2000 waxless stripping machines. However, in this case the knife, grippers and transport conveyor are all in the one apparatus. Figure 12 A to C provides a snapshot view of the movements of the new Robotic stripping wedge and its flexibility.

The permanent stainless steel cathode is presented in the stripping station already flexed and pre-opened, the robots then bring the knives in tip first until the blade is approximately 50mm past the top of the copper. At this point, the wedges start rolling to a vertical position whilst they are travelling in a downwards motion (the tips of the knives only mm away from the blade on each side). Once the wedge is down far enough to clear the hanger bar (shown by recess in wedge profile) the wedge is completely vertical and the rollers are touching the stainless steel blade keeping the knife edge away and unable to cause damage.

Figure 12B shows each of the wedges in the bottom position just before down ending. At this point the grippers are activated and the copper becomes clamped. Both wedges roll to horizontal about an imaginary axis which is perfectly aligned with the void in the copper envelope cause by the v-groove. Once horizontal, the wedges rise slightly and then pull away from each other separating the copper and transporting it away to a bundle, transfer conveyor, weighing device, reject bundle, sampling device or any other station the customer desires.



A B C

Figure 12 – Robotic Cathode Stripping sequence

Performance and Results

Testwork of separation efficiency to date has been outstanding. No flapping has been observed in the Robotic Stripping system when processing standard V- grooved stainless cathode plates, with laminated copper cathode. When processing stainless cathode plates prepared with significantly reduced V-groove condition and laminated copper deposit, a maximum 3 flapping motions were required.

If the copper did not separate on the first attempt, the robots "flap" the copper in a specific program sequence. Importantly, there is no bending in the copper and all the forces are concentrated in the same location leading to the vastly reduced flapping frequency.

With increased separation reliability, the average cycle times gets closer to the designed cycle times providing operators with satisfaction and guarantee that they will meet throughput and production requirements irrespective of copper deposit conditions.

Testwork on the Robotic Stripping prototype is ongoing, and in parallel it is used by the Xstrata Copper operating refining to process stainless cathode plates rejected from the commercial stripping machines.

Flexibility and Safety

The robots can be programmed to handle a variety of different situations minimizing manual input. They have the ability to perform a number of different processes (initiated by the push of a button) throughout the stripping cycle dependent on the copper condition and operator's desires.

The robots also have the automatically or by operator controls to safely remove the copper with out any manual handling of the copper or entry into the stripping area. This feature greatly improves operator safety. Furthermore, if the copper sheet is to be rejected for quality reasons, whether it be one side or both, the robots have the ability to transfer the single sheets to a separate reject bundle or any other customer desired location with in the robots reach. This feature, in combination with online cathode quality scanning devices, would provide significant materials handling benefits to the operation.

Applications / Implementation

The new Xstrata Technology Cathode Robotic Stripping system is extremely flexible and is suitable for both green field and retrofit applications. It would be very well suited to implementation in:

- Plants with variable copper deposits which may be difficult to strip
- Plants where manual sorting of reject cathode copper occurs.
- Refineries with un-reliable power supply or regular power outages during plating)
- Smaller scale production operations
- Tankhouses where time efficiency is extremely important and critical to project continuation
- Conversion of older plants from wax to waxless

Ongoing Development

Xstrata Technology understands the features of the new stripping process and robotic control provide potential for advantages in other areas of the tankhouse design and operation to gain better productivity and efficiency. Scope will include optimising the permanent cathode plate design due to more precise and flexible control when using robotics to achieve reduction in operating and capital cost. In conjunction, there is potential for further improvements to automation of crane lifting and handling systems.

Xstrata Technology continues to develop these concepts as part of its' ongoing research and development programs

Summary

The Xstrata Technology research and development program achieved the objective to create a more accommodating and universal stripping machine, for the production of spilt sheet cathode copper product. Implementation and installation of the next generation Xstrata Technology Robotic Cathode Stripping system has the following advantages:

- Reduced capital costs (reduction in conveyors and transfer equipment)
- Small foot print especially for stand alone units
- Can retrofit into existing machines with small modifications
- Easy to install and commission
- Provides operations currently producing split sheet ISA product bundles increased flexibility in the sequencing of normal harvesting operations and during smelter shutdown periods.
- Reduced noise (elimination of hydraulics, reduced impact noise from copper sheets)
- Increased time efficiency

- Flexibility with copper transport and rejection

Acknowledgments

We would like to thank all the staff involved from the Xstrata Copper, Townsville Refinery for their assistance during the testwork at CRL and recognise the extensive input by Jason Schulte, Blair Warry and Tony Ruddell from Xstrata Technology during the development process.

References

[1] Robinson, T., Davenport, W.G., Moats, M., Karcas, G. & Demetrio, S. (2007): Electrolytic copper electrowinning – 2007 world tankhouse operating data – Cu 2007, Volume V- Copper Electrorefining and Electrowinning, Eds. Houlachi, G.E., Edwards, J.D., & Robinson, T.G., Toronto, Canada, The Metallurgical Society of CIM.

[2] Moats, M., Robinson, T., Davenport, W.G., Karcas, G. & Demetrio S. (2007): Electrolytic copper refining – 2007 world tankhouse operating data – Cu 2007, Volume V- Copper Electrorefining and Electrowinning, Eds. Houlachi, G.E., Edwards, J.D., & Robinson, T.G., Toronto, Canada, The Metallurgical Society of CIM.

[3] Armstrong, W. (1999): The ISA PROCESS and its contribution to Electrolytic Copper – Rautomead Conference, Scotland.

[4] Okane, J. (1997): ISAPROCESS – Benchmarking Copper Refining Electrolysis – GDMB 33rd Metallurgical Seminar, Lunen, Germany.

[5] Donaldson, P.E. & Detulleo, J.J. (2003): Falconbridge's Kidd Copper Refinery Birthplace of the Kidd Process. An Update on the Refinery and Latest Developments – Copper 2003-Cobre 2003, Volume V- Copper Electrorefining and Electrowinning, Eds. Dutrizac, J.E. & Clement, C.G. Santiago, Chile, The Metallurgical Society of CIM.

[6] Matsuda, M., Goda, T., Takebayashi, K. & Maeda, Y. (2007): Recent Improvements at the Hitachi Refinery – Cu 2007, Volume V- Copper Electrorefining and Electrowinning, Eds. Houlachi, G.E., Edwards, J.D., & Robinson, T.G., Toronto, Canada, The Metallurgical Society of CIM.

[7] Sue Yek, G. (2008): Investigation of the Mechanical Forces of the Xstrata Technology Copper Cathode Roller Stripper – BE (MECH) Thesis, James Cook University, Townsville, Australia.

DEVELOPMENTS IN PERMANENT STAINLESS STEEL CATHODES WITHIN THE COPPER INDUSTRY

K.L. Eastwood and G.W. Whebell
Xstrata Technology
Hunter Street
Townsville, Australia 4811
keastwood@xstratatech.com.au

ABSTRACT

The ISA PROCESS™ cathode plate is characterised by its copper coated suspension bar, coupled with a blade employing austenitic stainless steel alloy 316L. The blade material has become the mainstay of the technology and has been closely copied by competing cathode designs. Improvement to the cathode plate design remains a key area for research, and ongoing developments by Xstrata Technology's ISA PROCESS™ have recently been commercialised. Two such developments are the ISA Cathode BR™ and ISA 2000 AB Cathode. The ISA BR cathode is a lower resistance cathode that has proven to enhance operating efficiencies. The AB cathode was designed to improve stripping inefficiencies in the ISA 2000 technology. These developments have now had time to mature and their long term performance will be discussed. Rising material costs and the desire to extend the operating boundaries of the standard 316L cathode plate has triggered a number of significant advances. These involve the use of different stainless steels as alternatives in some operational situations. The technical aspects and results of commercial trials on this development will also be discussed in this paper.

INTRODUCTION

The introduction of permanent stainless steel cathode technology was pioneered in the copper industry by IJ Perry and colleagues in 1978, with the introduction of the ISA PROCESS™ in the Townsville Copper Refinery, Perry [1]. While a number of parallel processes have emerged since its introduction, ISA Process Technology (IPT) has continued to be the mainstay electrolytic copper process with consistent improvements and superior operational performance.

Following the introduction of the ISA 2000, recent developments that have been offered to the market are the ISA BR and AB cathode plate. The BR plate offers a low resistance electrode that has the potential to significantly reduce power costs. The AB cathode was introduced to the market to improve stripping performances particularly where tankhouses with the ISA 2000 technology were prone to frequent power outages.

A new development soon to be introduced into the market is the use of alternative steels for cathode plates. Rising costs and the desire to extend the operating boundaries of the 316L alloy triggered investigations into alternate stainless steel types and their application to various copper electrolytic processes. The steels tested have the potential to reduce the capital cost of the cathodes while still providing a technically sound cathode. Tests have been carried out in diverse operating environments from small low-cost electrowinning operations to intensively managed electro-refining plants.

ISA CATHODE BR™ – "LOW RESISTANCE" PERMANENT CATHODE

BR Design

The BR cathode design extends the copper plating up to 55mm down the blade, compared to the standard ISA plate of 15-17mm. The extension of the copper plating reduces the amount of electrical resistance that exists between the copper plating and the solution line. This is achieved by reducing the distance the current has to travel through the stainless steel. The resistance of stainless steel is 74 μΩ.cm @ 50^0C compared to a value of 1.8 μΩ.cm @ 50^0C for copper.

The BR design can increase the average copper plating thickness from 2.5mm to 3.0mm. The increase in copper thickness increases the corrosion resistance of the plate. This is particularly advantageous in electrowinning applications where cathodes may be subjected to corrosive conditions.

Development of the BR cathode

Standard ISA cathodes, whilst superior in most aspects to alternate stainless steel cathode configurations have slightly higher resistance than solid copper hanger bar systems. While the lower resistance is attractive, deficiencies for some applications in the long term performance of the solid copper hanger bar were identified following a large scale trial at the Townsville Copper Refinery. Webb [2]

The initial development of the BR cathode, as reported by Webb [2], followed trials conducted to compare the performance of solid copper hanger bar cathodes and ISA PROCESS™ cathodes. These trails indicated that whilst ISA PROCESS™ cathodes gave higher current efficiencies of 2% to 2.4% (electro-winning and electro-refining respectively) the continuing market demand to produce copper more efficiently lead to the development of the lower resistance ISA cathode BR™.

Figure 1 – ISA cathode BR™

Additional Testing of the BR Cathode

In addition to the early work completed by Webb [2] the internal plate resistance of various cathode plates have been measured using a digital micro-ohmmeter at Townsville's Copper Refinery. To replicate cell conditions, cathode plates were plated with copper for a period of 24 hours then the resistance measured. The average plate resistances are shown in the graph below.

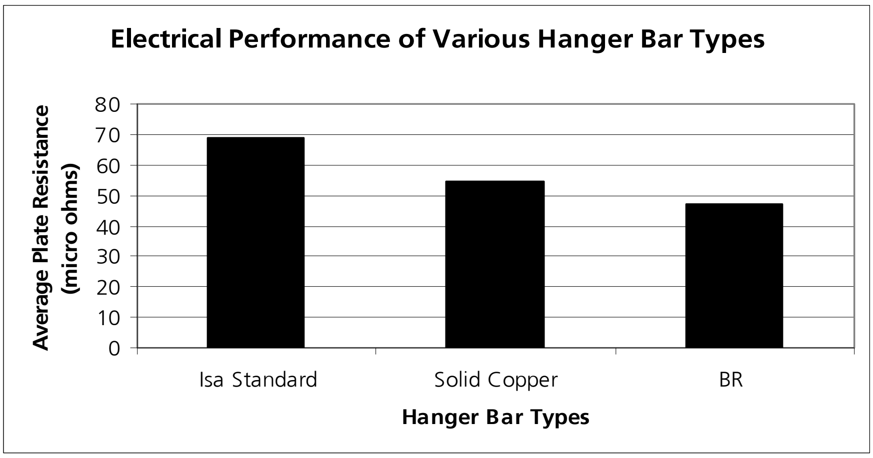


Figure 2 – Internal resistance of various hanger bar types

The measurements complemented Webb's [2] original work by confirming the ISA Cathode BR™ as the electrically superior plate, by exhibiting the lowest plate resistance.

Further operational measurements have been completed at other ISA PROCESS™ electrowinning facilities. All measurements confirm the previous work completed by Webb [2] at Compania Mineral Zaldivar showing a potential saving of US$100,000 per year in power costs could be achieved with the ISA Cathode BR™. This equates to a cost saving of approximately US$0.75 per tonne of copper produced.

Since the ISA BR™ cathodes introduction in the early 2000's, in excess of 106,000 BR configured plates have been produced, representing approximately 450,000 tonnes of copper per year. These plates have been installed in 6 plants in Japan, USA, Philippines and South America.

THE DEVELOPMENT OF THE AB CATHODE

The ISA 2000 Waxless System

To eliminate the need for wax as a bottom and side masking agent ISA PROCESS™ developed a waxless cathode design, now commonly known as the ISA 2000 technology.

The principle behind the waxless development lies within the 90° v-groove machined into it. This allows separation of the enveloped cathode into two separate sheets by the ISA PROCESS™ stripping machines. On a micro-scale, the copper crystals grow perpendicular to the cathode plate from opposing sides of the v-groove, causing them to intersect at right angles to each other. Where they intersect, a discontinuity in the structure is formed, resulting in weak zone, along which the copper splits.

Figure 3 details a microscope view of a copper cathode cross-section, taken from the v-groove region, magnified 10 times. The sample was polished and etched to show the copper crystal structure. The white lines indicate the orientation and direction of crystal growth.

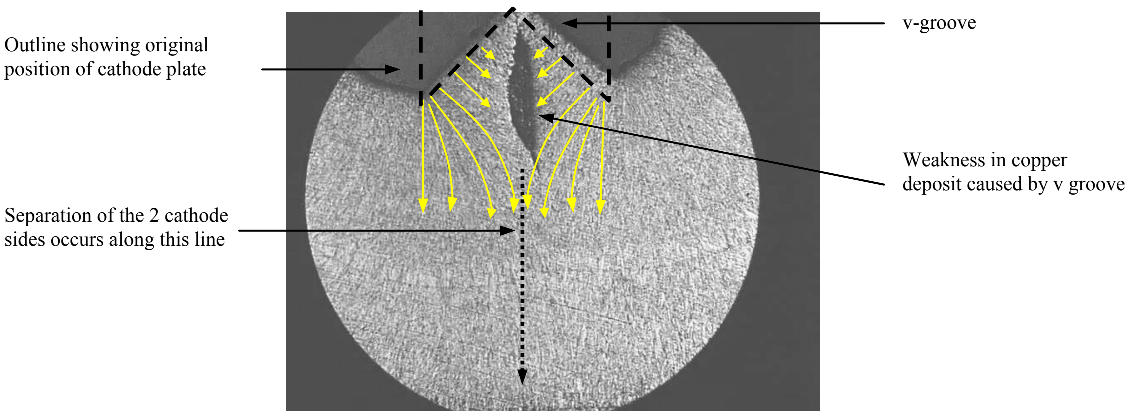


Figure 3 - Microscope view of cathode deposit cross-section in the v-groove region.

In addition to this effect it is believed in electrowinning facilities small gas bubbles (oxygen from the anodes) become trapped in the groove. This gas layer then serves as an insulating layer between the two growing faces.

The v-groove splitting mechanism combined with modifications in the stripping machines has been extremely effective in the separation of copper cathodes under most circumstances.

The AB Design

The AB cathode design has 45 degrees chamfered corners cut away from the bottom of the blade. The "v" groove runs the length of the blade and up the chamfered corners. The dimensions of the chamfered corners are 60mm x 60mm. These dimensions have been chosen to maximise the tearing action, whilst reducing the chances of bending the cathode corners or producing a ropey edge that would potentially entrap falling slimes. The tearing action produced by the corner chamfers initiates the split of the copper sheets and improves splitting if lamination has occurred.

The edgestrips designed for the AB cathode are a cross slot edgestrip with a moulded bottom plug. The internal dimensions of the plug have been specifically designed for the AB cathode and allow the edgestrip to fit securely onto the AB plate to prevent nodule growth.

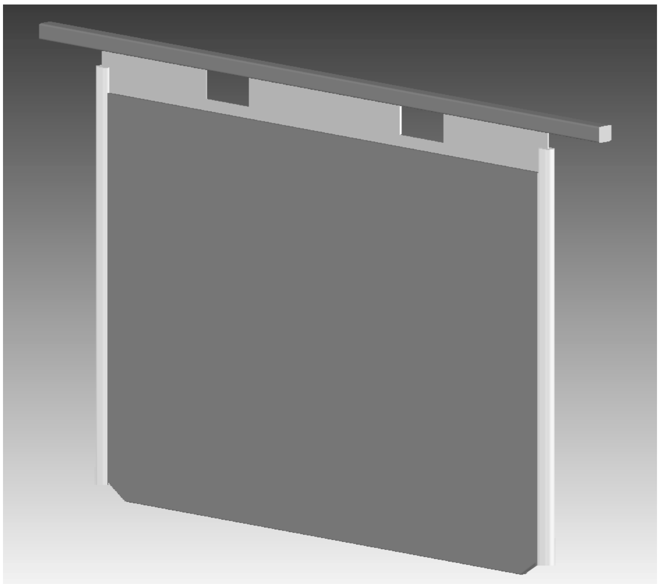


Figure 4 – AB Cathode

The AB concept was initially developed for electrorefining to:

- Reduce stripping inefficiencies if tankhouses were prone to power outages.
- Improve the life of an ISA 2000 edgestrip.
- Prevent end cap damage.

Power outages alter the initial growth pattern of the copper. When the power is resumed the new growth pattern of the crystals laminates the original copper growth. The resulting lamination can null the effect of the v groove. This can increase stripping times as cathode sheets may require additional movements in the stripping machine to split the enveloped copper. The effect power outages have on the cathodes stripping performance is dependant on the duration, the time in the cycle and the anode overlap. The AB cathode design aimed to reduce the stripping inefficiencies caused by power outages.

In the ISA 2000 cathode plate the bottom corners have square notches of steel removed. The edgestrips have moulded plastic end-plugs, which fit neatly into the voids formed by the notches in the plate. This system eliminates copper nodule growth from the bottom corners. After the early commercialisation of the ISA 2000 technology there were a large number of end cap failures as well as a reduction in the edgestrip life in some refineries. In the standard wax technology the edgestrips do not contact the traverse conveyor and therefore less stress is placed on the edgestrips. The ISA 2000 edgestrips are in direct contact with the traverse conveyor potentially increasing the stresses on the edgestrips. In the AB cathode design the edgestrips do not contact the traverse conveyor.

Experimental Testwork

IPT developed a number of prototypes of the AB cathode based on a 60mm x 60mm chamfer. The results were positive with the corner chamfer reducing stripping inefficiencies when power outages caused lamination of the copper.

At the Townsville Copper Refineries, a cell of 44 AB cathodes were installed and stripped weekly. They were monitored for stripping difficulties, defined by additional movements required by the down ending station to ultimately remove the copper cathode. These additional movements were commonly known as "flaps". The results from these trials are summarised in Tables 1 and 2.

Table 1 - Stripping data under standard test conditions.
No power outages included.

	No. flaps / 100 strips
AB Cathode	3.3
Standard Cathode	4.2

Table 2 - Stripping data when severe laminations have occurred during the plating cycle.

	No. flaps / 100 strips
AB Cathode	17.3
Standard Cathode	38.5

Under normal operating conditions the standard ISA 2000 cathode plates effectively separated the copper sheets and therefore the improvements were minimal.

The AB cathode improved stripping performance significantly when power outages had laminated the enveloped copper sheets. The additional “flaps” were reduced by half with an AB cathode.

The trials were then extended to include corners of varying shapes and sizes. Smaller corner cut outs as well as rounded corners were trialled. Results indicated that corner chamfers smaller than 40mm x 40 mm and rounded corners performed poorer than a standard v grooved ISA cathode under normal operating conditions. The larger chamfered corners were found to aid stripping performance however were prone to bending over time.

The AB cathode design eliminates the plastic edgestrip contacting the traverse conveyor, reducing fatigue cracking and potentially improving the life cycle of the edgestrips. AB cathodes in service in the Townsville Copper Refinery with an end cap design have been in service for 1.5 years without failure.

As the edgestrips no longer contact the base of the traverse conveyor the v groove is in direct contact with the traverse. Accelerated tests were completed to identify whether any deterioration in the v groove occurred.

An AB plate was lifted and then lowered on to the traverse conveyor a total of 728 times, equivalent to 14 years in service. The impact points on the plate were marked and the measurements were taken from these points through out the test. It was then placed back into service and the plate's performance monitored. Table 3 represents the data collected.

Table 3 - Results from v groove deterioration testing.

No of lowers	Service time	v groove measurements 3 points			Comments
0	0	1.38	1.51	1.52	
208	4 years	1.37	1.37	1.46	slight curling R/H and Mid
312	6 years	1.35	1.32	1.42	slight curling, small chips
468	9 years	1.3	1.29	1.28	curling of contact point edges
728	14 years	1.29	1.34	1.25	no observable change

After the equivalent of 14 years in service the v groove measurements decreased from 1.52 to 1.25 in this area. The tests were undertaken in the ISA PROCESS™ waxless demonstration machine. This machine, unlike production machines does not have a proportional speed control valve to allow the plate to be lowered gently onto the conveyor or soft metal pads for the plate to sit on. The plate descends rapidly onto the steel conveyor therefore making the action far more severe than a production machine. The plate continued to strip successfully after the testwork. This test was completed on several occasions with similar results.

Recently commissioned with the ISA 2000 AB cathode was Sumitomo’s Toyo Refinery in Japan. Approximately 22,000 plates have been manufactured and installed and are reported to be working efficiently. The edgestrip life is also being monitored.

ALTERNATIVE LOWER COST CATHODE PLATE

Current ISA blade material

The standard ISA blade is made of austenitic stainless steel, of grade 316L. It specifically contains 2-3% molybdenum for increased resistance to pitting, and has a low carbon content (0.03%) to minimise chromium carbide precipitation, or sensitisation of welded zones. This decreases the tendency for intergranular corrosion. The typical analysis of 316L is shown in Table 4, [3].

Table 4 – Blade Composition

Element	Composition %
Cr	16-18%
Ni	10-14%
Mo	2.0-3.0%
C	≤ 0.03%
Mn	≤ 2.0%
N	0.04%

The blade is 3.25 mm thick. Based on experience, this is the optimum thickness taking into consideration the plate performance, ease of manufacture and cost-effectiveness. The surface finish is a standard 2B manufacturing finish with a specific surface roughness in the range of 0.25 to 0.6 microns Ra. The high corrosion resistance of the cathode plate is provided by a very thin, tenacious, self repairing layer of chromium oxide, which forms a passive film on the blade, [3].

The development of a lower cost cathode

While the 316L alloy has been the mainstay of the technology since its development in 1978, rising costs and operational considerations in some plants have triggered the ISA PROCESS™ to examine the use of alternative stainless steels in the copper electrorefining (E/R) and electrowinning (E/W) industries.

Increasing costs of metal prices, namely nickel and molybdenum continue to push 316L prices higher and therefore the need for alternative steels suitable for use in the industry was desirable.

The life cycle cost of a cathode was also a consideration in the development of an alternative cathode blade material. The ISA cathodes were developed for a 10-15 year life cycle. Some operations however have a considerably shorter life span and a more economic plate with a life cycle matching the project life would be an advantage. In addition, the extreme operating environments in some plants require plates to be replaced or repaired after 3-4 years.

The focal point of the development work has been on testing a relatively new type of duplex steel, LDX 2101 and the standard 304L stainless steel.

LDX 2101, DUPLEX STAINLESS STEEL

LDX 2101 is a low-alloyed, duplex stainless steel. Its microstructure contains approximately equal amounts of ferrite and austenite. A typical analysis of the duplex steel is Table 5, [4]

Table 5 – Blade composition

Element	Composition %
Cr	21.5%
Ni	1.5%
Mo	0.3%
C	≤ 0.03%
Mn	5%
N	0.22%

LDX 2101 has high mechanical strength due to its duplex microstructure and high nitrogen content. The corrosion resistance is in general at least as good as that of Cr– Ni grades such as 304L and in some cases as good as Cr-Ni-Mo grades such as 316, [4]. The reduction of molybdenum and nickel content reduce the overall price of the steel.

Experimental Testwork

Chemical Resistance Testing

A series of corrosion tests were completed by the Avesta Development Group. LDX 2101, in both a linished and unlinished surface finish was compared against the standard 316L steel and 304L stainless steel. The test parameters are represented in Table 6 and 7.

Table 6 – Test solutions for immersion tests

		Base	1	2	3	4	5	6	7
Cu	g/L	45	45	45	45	45	45	45	45
H_2SO_4	g/L	160	**175**	**195**	**235**	160	160	160	160
Chloride	ppm	40	40	40	40	**55**	**70**	**100**	**120**
Temp	^{o}C	50	50	50	50	50	50	50	50
Thiorea	ppm	2	2	2	2	2	2	2	2

Table 7 – Test solutions for immersion tests

		8	9	10	11	12	13	14
Cu	g/L	45	45	45	45	45	**15**	45
H_2SO_4	g/L	160	160	160	**175**	**195**	140	195
Chloride	ppm	40	40	40	**70**	**100**	40	100
Temp	^{o}C	**60**	**68**	**72**	**60**	**70**	50	70
Thiorea	ppm	2	2	2	-	-	-	-
$Fe_2(SO_4)_3$	g/L							**6**

The bold values represent the parameters that were altered from the base line test. The test steels were immersed for 30 days in all tests. Dickson [5] has shown "no uniform corrosion was detected on any of the stainless steel grades in any of the test solutions. No corrosion rate exceeded 0.01mm/year. No localised attacks, such as pitting or crevice corrosion were observed".

Strength

The LDX is superior in mechanical strength to the 316L stainless steel. The superior strength has allowed plates to be manufactured using a thinner steel sheet. The minimum thickness acceptable is still under investigation. The strength of the steel prevents the manufacturing of plates greater than 3mm thickness. The reduction in thickness, without compromising the strength of the cathode reduces the manufacturing cost of the cathodes.

Flatness Tolerance

The flatness tolerance of commercially available LDX steel is not acceptable for use as cathode plates. Development work in the manufacturing of the steel has allowed the flatness tolerances to fall within acceptable limits.

Surface Finish

The 2B finish has been a successful surface finish for the standard 316L cathode plate. Voids in the surface finish allow the copper to "key" into the steel. This facilitates the adhesion of the copper to the stainless steel in the plating and harvesting cycle, yet permits easy removal once the plate is flexed. Figure 5 is an SEM micrograph showing the 2B surface finish of 316L.

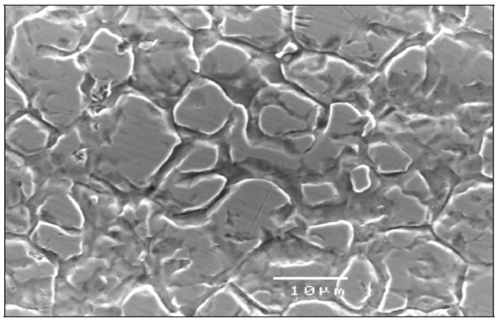


Figure 5 - SEM of 316 L surface magnified 2000x
MacDonald [6]

The nature of the duplex steel does not permit a standard 2B surface finish. A tenacious oxide layer prevents the 2B film from being achieved in the manufacturing process, MacDonald [6].

The achievable mill finishes on the duplex steel do not facilitate the successful adhesion of copper. In tests completed at the Townsville Copper Refineries pre-stripping occurred with a standard duplex mill finish. Figure 6 represents a typical mill finish of the duplex steel.

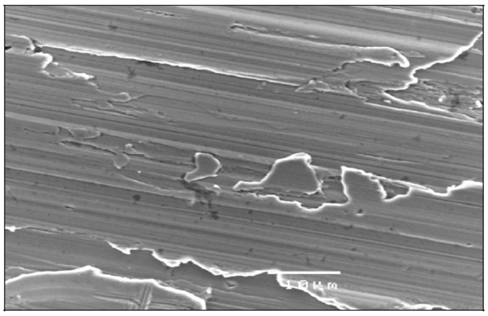


Figure 6 - SEM of LDX 2101 mill finish magnified 2000x MacDonald [6]

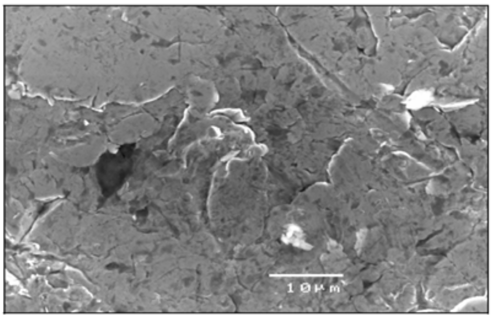


Figure 7 - SEM of LDX 2101 modified surface magnified 2000 x MacDonald [6]

The steels surface has limited voids for the copper to attach itself to. To facilitate the adhesion of copper to the LDX, IPT has developed a unique surface finish for use in the E/R and E/W of copper. An example of this modified surface is presented in Figure 7. Testwork has revealed optimum Ra (surface roughness measurement) values vary for E/R and E/W conditions due to the nature of the copper deposit. The surface finish can therefore be tailored to suit a specific operation.

Operational testing of the LDX 2101 steel

Approximately two cell loads (62 cathodes) of trial plates were manufactured with the LDX 2101 and placed into service at a small electro-winning facility in Australia.

An average analysis of the plants electrolyte conditions are shown in Table 8.

Table 8 – Average analysis of E/W tankhouse

Cu	38-45g/L
H_2SO_4	160-170g/L
Cl	20-30ppm
Mn	90ppm

The cathodes have been in service since the beginning of June 2006 and their physical properties and stripping performance have been monitored. Under standard operating conditions there have been no concerns with the plates.

304 STAINLESS STEEL

The standard 304L stainless steel with a 2B finish was tested in Townsville's Copper Refinery. The plates have been circulating for over 1.5 years with no concerns.

Accelerated corrosion tests were also completed on the steel. Table 6 and 7 represents the immersion tests completed. No uniform corrosion was detected on any of the stainless steel grades in any of the test solutions. No corrosion rate exceeded 0.01mm/year. No localised attacks, such as pitting or crevice corrosion were observed, Dickson [5].

CONCLUSION

Through ongoing development work the ISA PROCESS™ has continued to improve on the original cathode plate design. Past and present testwork still suggests the ISA cathode BR™ is the lowest resistance cathode on the market and the AB cathode has effectively reduced stripping inefficiencies in the ISA 2000 technology.
The development of the LDX 2101 as an alternative steel in cathode plates has the potential to reduce capital costs for end users while still providing a technically sound cathode.

ACKNOWLEDGEMENTS

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REFERENCES

1. I.J Perry, J.C Jenkins and Y. Okamoto, "The Use of Stainless Steel Cathodes at Copper Refineries Pty. Ltd", Townsville, AIME Annual Meeting, Chicago U.S.A, 1981

2. W.Webb and J.Weston, "The development of a "Lower Resistance" Permanent Cathode", Minera Chilena March April 2003 (Spanish) (English version available at www.xstratatechnology.com)

3. D. Peckner and I.M. Bernstein, Handbook of Stainless Steels, McGraw–Hill Book Company,USA,1977

4. Outokumpu Stainless AB, "Data Sheet LDX2101 Duplex Stainless Steel", Sweden

5. C. Dickson, A.Iversen, A.Wallin and I. Hedstrom "Stainless Steel Cathodes in Copper Refining – Immersion Tests in Customer Defined Solutions",Report prepared for internal distribution, Avesta Reserch Centre, 2006

6. L. MacDonald, "Stainless Steel in Copper Electrolyte Solutions", Thesis Report, James Cook University, Townsville, Australia 2006

TANK HOUSE EXPANSION AND MODERNISATION OF COPPER REFINERIES LTD, TOWNSVILLE, AUSTRALIA

Presented at Alta Conference, Adelaide, Australia, 2000

Brendan O'Rourke
Operations Manager
Copper Refineries Pty Ltd
Townsville, Queensland 4810 Australia

CONTENTS

1.0 INTRODUCTION

Mount Isa Mines was originally founded on a series of Lead, Silver and Zinc ore bodies in 1923. In 1955 significant adjacent copper orebodies were defined. The unique polymetallic nature of the Mount Isa Mines operations commenced.

In September 1959 a subsidiary copper refinery company, Copper Refineries Pty Ltd commenced conventional "starting sheet" production and export of 40,000 tonnes per annum. A series of two major expansions lead to operating capacity of 80,000 tones per annum in 1966 and 150,000 tonne in 1975.

The first commercial introduction of the "ISA Process" permanent stripping technology was commissioned in 1978. Cathode production capacity was also increased to 170,000 tonne per annum. The vastly improved electrode alignment and accuracy inherent with the Permanent Stainless Steel Cathodes of the ISA Process then allowed the capacity of the Refinery to be increased to 210,000 tonne per annum by 1996.

The 1997 commissioning of the 51% Mount Isa Mines owned Ernest Henry Mine and the concurrent expansion of operations at Mount Isa afforded the opportunity to expand and modernise the Copper Refineries operation.

After 20 years of ISA Process tank house operation and 15 years experience in exporting the ISA Process technology Copper Refineries was in an enviable position with respect to design options for a world class facility. Experienced gained in tank house layout, machine design and operational philosophies was easily applicable.

The Refinery upgrade activities commenced in December 1996 and were completed in April 1999. An annualised capacity of 270,000 tonne per annum was achieved by July 1999.

2.0 PROCESS SELECTION

2.1 LAYOUT

Various combinations of tank house layout and design have been implemented in ISA Process tank houses. Copper Refineries was constrained in many cases due to the fact that a full retrofit had to be conducted with a minimum of disruption to the existing operation. For example the location of receipt and delivery services for anodes and cathodes were fixed. The layout selected incorporates one crane per aisle feeding to and from a centralised machinery bay.

2.2 DESIGN CRITERIA

Design objectives were related to:

- Long Term Production forecasts.
- Customer requirements.
- Copper Refineries Pty Ltd Operations Survey.
- Construction in an existing operating plant.
- ISA Process technology developments.

2.2.1 Long Term Production Forecasts

With the commissioning of the Ernest Henry mine and the expansion of the Mount Isa Copper Mine into the Enterprise orebodies an annual operating capacity of 270,000 tonne per annum was required.

Concurrent with these mine expansions the Mount Isa based copper Smelting facilities have been upgraded. Improvements include, an extra oxygen plant to provide increased primary smelting throughput, stacker reclaiming concentrate blending facility, a fourth Pierce Smith converter together with a new anode casting wheel and rotary holding vessel.

2.2.2 Customer Requirements

Accredited with ISO9002 in 1994, Copper Refineries has a proven quality system to ensure the satisfaction of our customer base. Modernisation of the cathode stripping machines allowed the introduction of improved cathode bundle appearance handling and shipping. Requirements in terms of individual cathode weight, labelling, sampling and corrugation were highlighted.

2.2.3 Operations Survey

An extensive series of surveys was conducted with all operating personnel to ensure that problem areas with the existing operation were addressed. Operational improvements were identified in material movement, machinery access, slimes handling and reagent dosing. Over 350 suggestions were logged into a database to provide for key design criteria.

2.2.4 Construction in an Existing Plant

The requirement to minimise production disruption dictated that new electrode handling equipment be commissioned prior to removal of the superseded equipment. Conversion of the electrolyte and cell systems was conducted in a series of intensive shutdowns that were coincided with planned shutdowns at the Mount Isa Copper Smelter. A key design element in the electrolyte and bus bar systems was ease of installation.

2.2.5 ISA Process Technology Improvements

The Cathode Stripping Machines have provision for improvements in the edge masking system utilised in the ISA Process. These improvements relate to the elimination of bottom wax on the stainless steel cathode blanks. This concept is now marketed as ISA Process 2000.

2.2.6 Final Process Selection

The expansion and modernisation of the Copper Refineries tank house was implemented with the following items:

- Replacement of 1024 lead lined cells with 1162 polymer concrete cells.
- Total replacement of electrolyte, slimes and DC electrical reticulation.
- Installation of section switches
- Installation of Decant Filtration and “Quick-Fill” operation.
- Centralised reagent batching and distribution.
- Replacement of Anode Scrap Machine with new machinery that incorporates single piece washing.
- Replacement of Anode Preparation Machine with new machinery incorporating lug milling and buffered storage capacity.

- Replacement of Cathode Stripping Machines with new machinery incorporating inline bundling, weighing and strapping.
- Replacement of six manually operated cranes with two automated cranes utilising pyramid based locating devises.
- Installation of a real-time cathode weighing , loading and despatch computer system

3.0 PROCESS DESCRIPTION

3.1 Modernised Refinery Operating Statistics

Capacity	270,000 tonnes per annum
Cells	1162
Electrolyte Temperature	63^0c
Cell Flow Rate	25-30 litres per minute
Anodes	45
Cathodes	44
Electrode Pitch	95mm
Maximum Anode Weight	410 kg
Maximum Cathode Weight	115 kg
Anode Cycle	21 days
Cathode Cycle	3 x 7 day or 10/11 day
Number Rectifiers	4
Current Density	305 A/M^2
Electrical Circuits	3
Electrolyte Circuits	3
Number of cranes	2

3.2 TANK HOUSE LAYOUT

The Cathode Stripping Machines were relocated from their positions at the extremities of the building to be centrally located. The anode and scrap handling functions are also located in the centre of the building.

A machinery annex was added to the building to locate all of the electrode handling machines. This design was required to meet the same side anode receipt and cathode, anode scrap despatch design requirement. Six aisle trolleys transport electrodes into and out of the machine annex. The machinery annex has two small auxiliary cranes installed to allow for heavy equipment maintenance, reject cathode plate removal and transport of stripping machine consumable items.

The incorporation of the machinery annex into the layout designs meant that the tank house only needed to be extended by one bay to accommodate the extra 138 refining cells. The extra bay was also required to facilitate the introduction of the new overhead cranes and the removal of the redundant cranes.

3.3 OVERHEAD CRANE OPERATION

Two Kunz fully automated overhead cranes handle all refinery stripping operations. These utilise a locating bale onto a fixed pyramid to achieve accurate electrode alignment. The capacity of the cranes will allow for lifts of 45 anodes at 410 kg each. The crane is capable of multiple tasks. Individual lifts of anode, anode scrap or cathode plates are possible with a dual lifting bail arrangement.

A laser-based device communicates via a central supervisory logic controller the operation status of all cranes and electrode handling machines. This communication linkage allows for safe and efficient stripping operations to be conducted and scheduled with a minimum of down time and operator intervention. Programmed sequences for all stripping operations are installed in the cranes scheduling logic controller.

3.4 ANODE PREPARATION MACHINE

Anodes are received at the Townsville Refinery from Mount Isa via rail and road. The new Anode Preparation Machine was supplied by Finland's Outokumpu Oy. The anodes as received are loaded via fork lift to the preparation machine for weighing, blade pressing, lug offset pressing and milling

Milling is both face and underside to provide improved anode verticality and current distribution. When combined with lug offset pressing it is possible to present a high weight, vertically aligned anode to the automatic Kunz crane.

The prepared anodes are then transported to a live storage facility via two automated trolleys. From the live storage area the anodes are either fed directly to the tank house Load-Out beams or placed into an assigned storage location.

The live storage feature of the installation allows the anode preparation function to be independent of the refinery stripping operations. This gives enormous flexibility to scheduling of anode receipt labour and a vast reduction in anode double handling.

3.5 ANODE SCRAP MACHINE

Anode Scrap is remove from the refinery for subsequent remelt at the Townsville site. The new Anode Scrap Machine was supplied by Mesco, Japan. Anode scrap bundles are presented to a fork lift interface for removal to the anode casting operation.

The new machine incorporates single blade washing with a three stage washing process. Three separate settling tanks are used to maximise recovery of slimes with wash water volume make-up supplied via a final rinse station. An innovative "grizzly" arrangement is located below the traverse conveyor to allow safe and efficient removal of any fallen scrap. This arrangement is serviced by one of the machinery annex auxiliary cranes.

3.6 CATHODE STRIPPING MACHINES

Two new Cathode Stripping Machine were supplied by Mesco, Japan. The new machines incorporate all features identified from customer surveys. Features that have been introduced are cathode corrugation, automatic sampling, inline sworn weighing, bundle labelling and strapping. Fully prepared cathode bundles are presented to a forklift interface.

Control of these features has been linked to an existing commercial scheduling and invoicing computer system to ensure cathode bundles are prepared to Customer Specification. Despatch and invoicing documentation is also produced by the same system.

3.7 ELECTROLYTE CIRCULATION

The operations survey identified many deficiencies in the existing circulation systems. The replacement of all the old lead-lined concrete cells afforded the opportunity to upgrade the circulation system. Polymer concrete cells were supplied by CTI Pacific Pty Ltd.

For operation at increased current densities a higher cell electrolyte flowrate is required. New circulation pumps and larger diameter piping was installed. The electrolyte piping installed is a fibre reinforced vinyl ester resin base supplied by FibreTec Australia. Over 3,500 metres of piping was installed. Individual cell feed valves provide for quick-fill operation on each refinery cell.

Decant collection and filtration has been introduced to the refinery operation. Separate decant collector boxes and Scheibler filters have been installed.

3.8 ELECTRICAL RETICULATION

The original electrical bus bar system installed at Copper Refineries Pty Ltd was not suitable for any further increase in operating current density. A 4 copper plate laminated bus bar system was installed together with full load section switches. The section switches were supplied by Hundt and Weber, Germany and are capable of full load switching at 30,000 Amps. Over 400 tonnes of copper bus bar were installed.

4.0 CONSTRUCTION

In all cases the scheduling of construction activities was dictated by cathode production requirements. This meant that cell, electrolyte circulation and bus bar system replacements had to be conducted in intensive shutdown periods, that coincided with planned production shutdowns.

The major construction milestones are listed below:

- April-June 1997 Crane runway beams strengthened.
- Sept-Oct 1997 Replacement of two electrolyte circuits – 600 cells
- Feb-May 1998 Construction of Machinery Bay Annex and machine runways beams.
- May-June 1998 Installation of Mesco supplied CSM's and ASM
- Aug-Sept 1998 Removal of old Cathode Stripping Machines.
- Aug-Sept 1998 Installation of Kunz cranes and replacement of crane rails.
- Sept-Oct 1998 Replacement of one electrolyte circuit - 424 cells.
- Sept-Oct 1998 Installation of Outokumpu supplied Anode Preparation Machine.
- January 1999 Removal of old APM and ASM.
- February 1999 Installation of additional 138 Refining Cells
- April 1999 Removal of six old overhead cranes

The activities were conducted with minimal production losses and over 500,000 Contractor Manhours without a lost time injury. This was only made possible due to the close cooperation and teamwork between the refinery and construction personnel.

5.0 COMMISSIONING

A dedicated commissioning team was setup to ensure a smooth transition from old to new equipment. Successful completion of several construction activities required a timely commissioning schedule for the major electrode handling machines.

The key commissioning milestones are listed below:

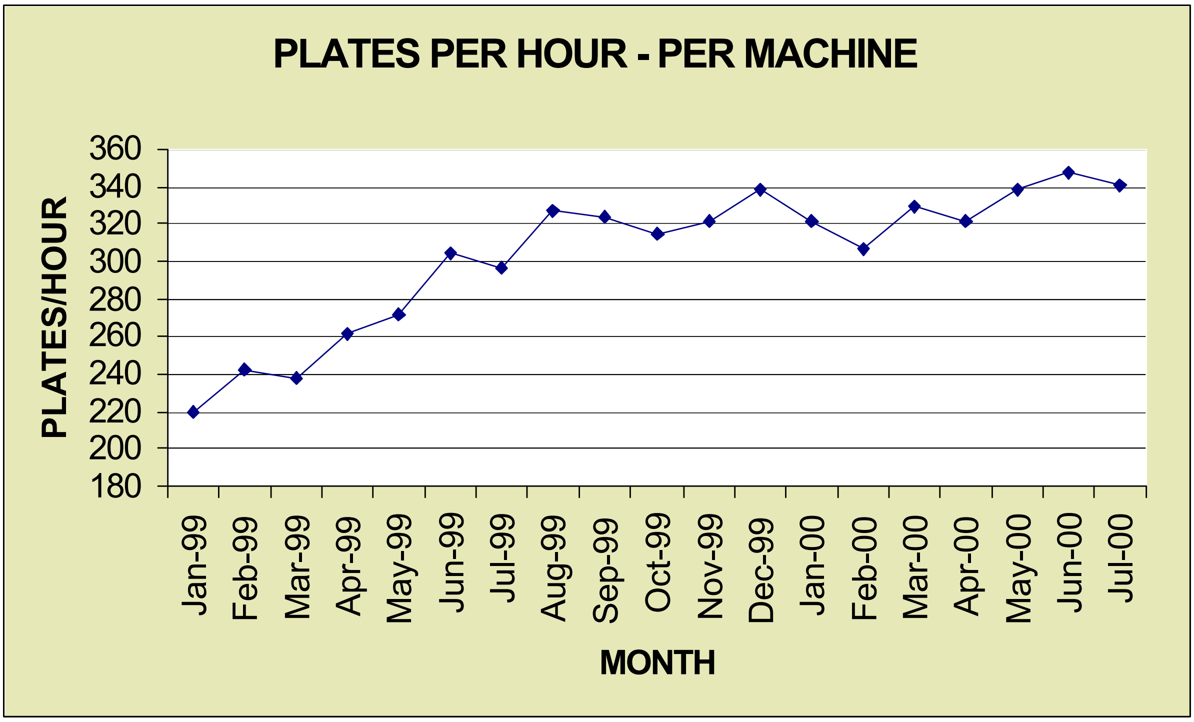
- July 1998 — Commissioning of Mesco supplied machines commenced.
- September 1998 — Acceptance tests for two Cathode Stripping Machines and Anode Scrap Machine completed.
- October 1998 — Partial commissioning of Kunz cranes commenced.
- November 1998 — Commissioning of Anode Preparation Machine commenced.
- November 1998 — Full-load Commissioning of Kunz cranes commenced.
- December 1998 — Acceptance tests for Anode Preparation machine completed.
- January 1999 — All Production operations converted to Kunz Cranes.
- February 1999 — Acceptance tests for Kunz cranes completed.

Commissioning engineers were provided by the three suppliers, Mesco, Outokumpu, and Kunz. Refinery Operating and training schedules were also developed by the Commissioning group to ensure that the overall construction schedule could be achieved.

6.0 PRODUCTION AND OPERATIONAL IMPROVEMENTS

The tables below detail the production performance of the new refinery since 1998. The step change improvement in early 1999 came about by the simultaneous introduction of milled anodes and the Kunz cranes to the refinery.

Further increases in output have been due to refining intensity increases. These increases are now possible due to the removal of previous anode weight constraints. Future intensity increases are planned as the Mount Isa Copper Smelter increases output to 270,000 tonnes per annum.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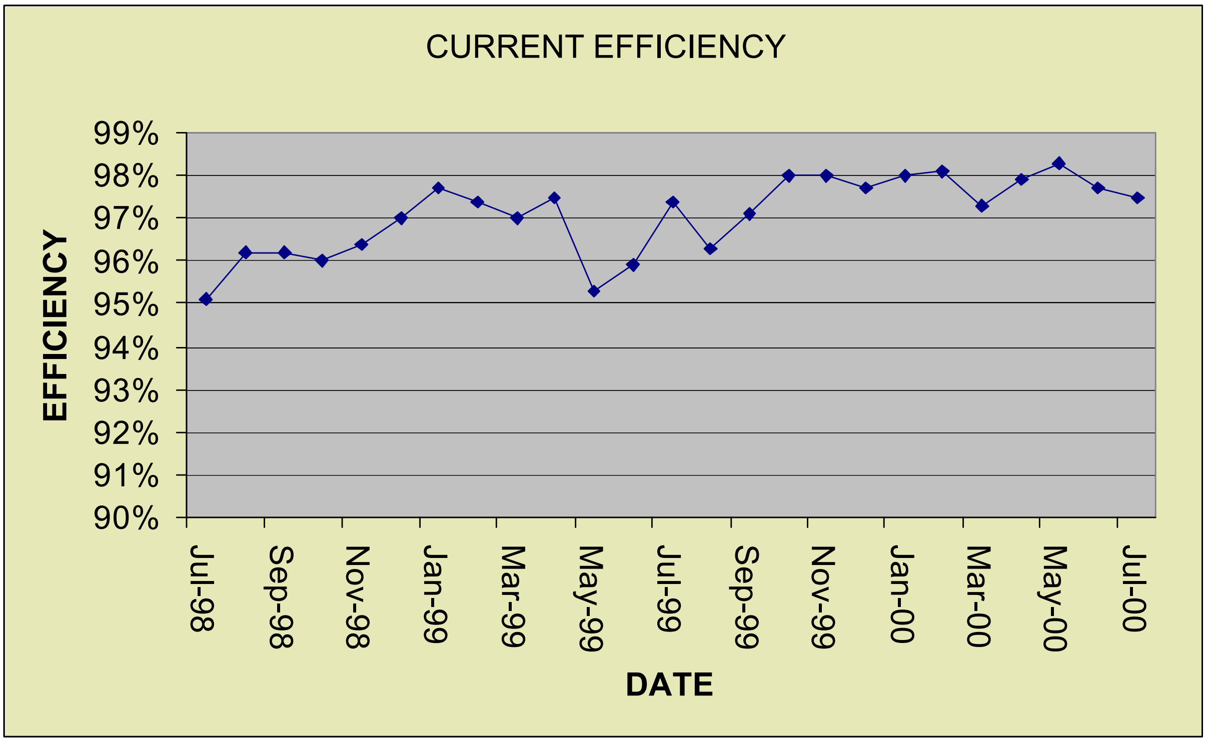
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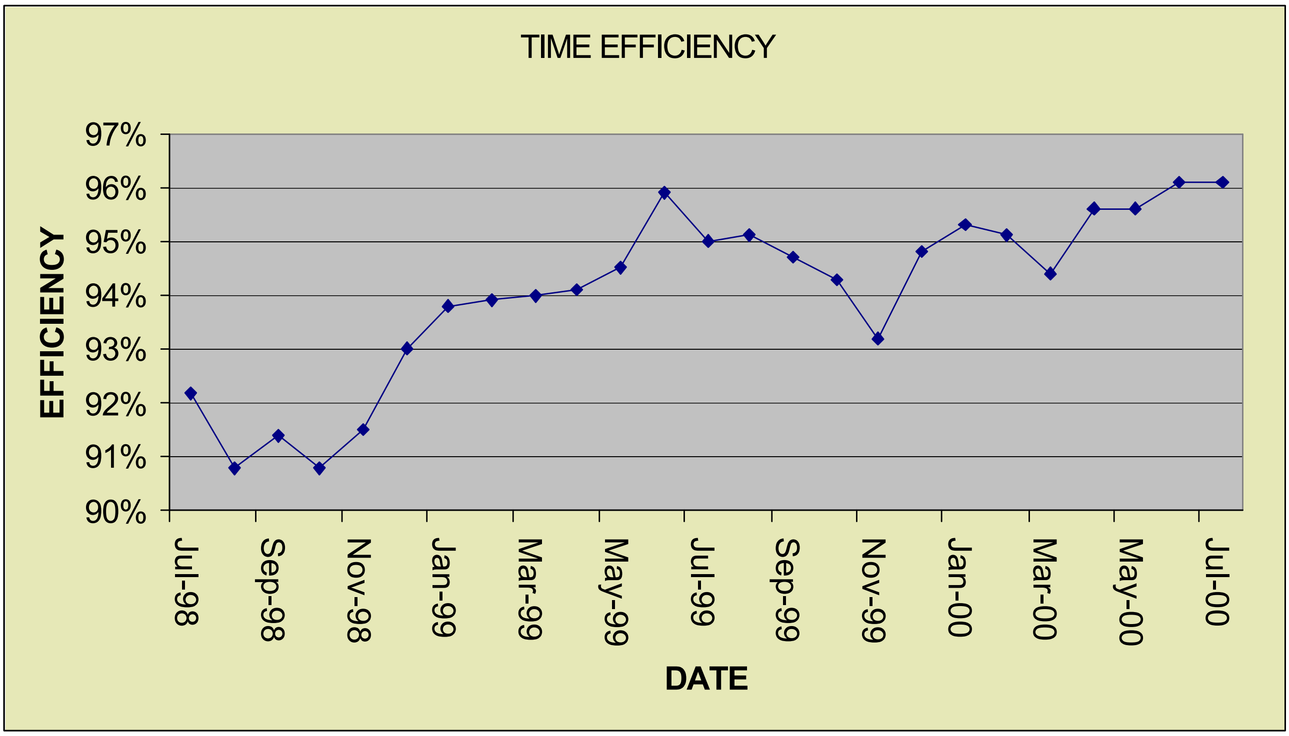
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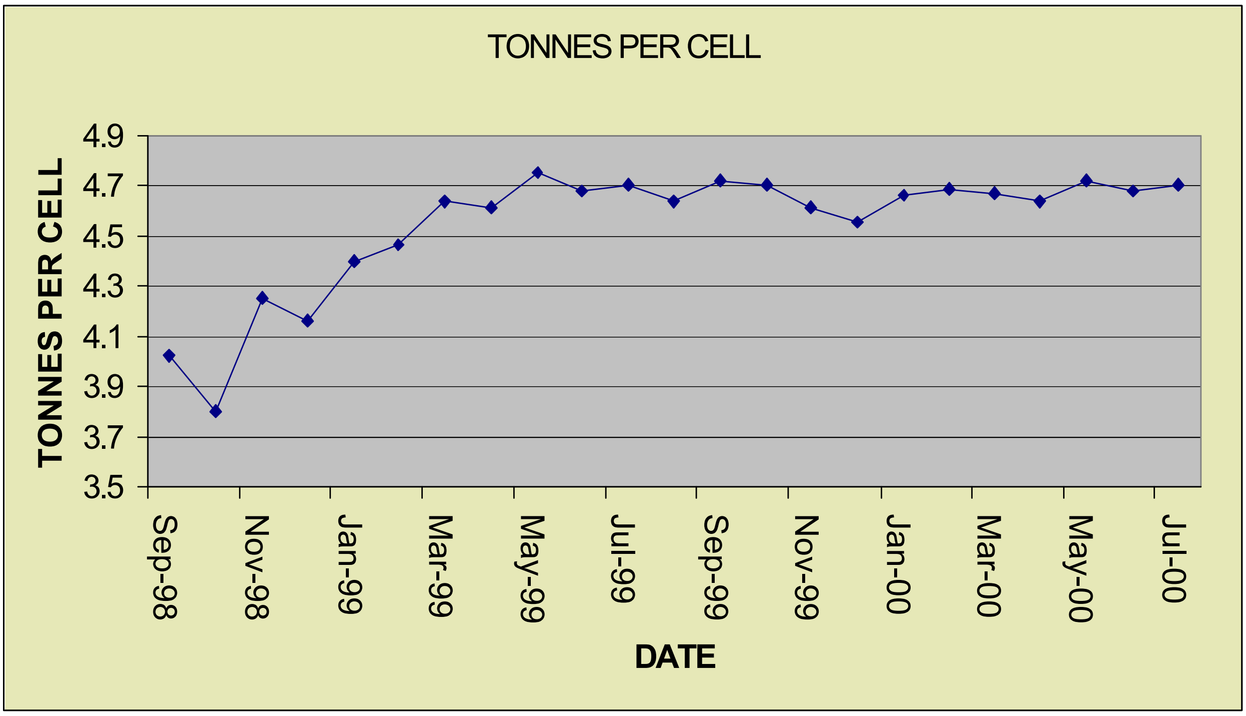
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7.0 REFERENCE

1. M Landan, H Traulsen, "The New Copper Tank House at Norddeutsche Affinerie", Copper 91/Cobre91 Volume III, Hydrometallurgy and Electrometallurgy of Copper, W C Cooper, D J Kemkpk, G E Lagos and K G Tan, Eds., Pergamon Press, Oxford, England, 1991, 517-526.

2. R Dobner, M Schwill, "Modernisation and Extension of a Conventional Tank House," Erzmetall, Vol 48, 1995.

3. J O'Kane, "ISA Process – Benchmarking Copper Refining Electrolysis," Paper presented at the GDMD 33rd Metallurgical Seminar, Lunen, Germany, November 19-21, 1997.

4. B.O'Rourke, "Copper Refineries Limited – Refinery Expansion," Paper presented at the 6th ISA Process Users Conference, Townsville, Qld Australia, June 20-22 1999.

5. W Armstrong, "ISA Process 2000", "Paper presented at the 6th ISA Process Users Conference, Townsville, Qld Australia, June 20-22 1999.

6. B.O'Rourke, "Tank House Expansion and Modernisation of Copper Refineries Limited," Paper presented at Copper-Cobre 99 Conference, Phoenix, United States, October 9-12 1999.

The development of a "lower resistance" permanent cathode (ISA Cathode BR™)

Wayne Webb

Executive - Research & Development
ISA PROCESS Technology

Joanne Weston

Metallurgical Engineer
ISA PROCESS Technology

ABSTRACT

The use of a permanent stainless steel cathode for the electrowinning and electrorefining of cathode copper is a well-accepted technology. As the developers of this technology, the ISA PROCESS Technology (IPT) has continued to improve the technology and maintain leadership.

As the pressure to produce cathode copper more efficiently has increased in the market place, IPT has recognised the need to develop a more efficient cathode plate.

The IPT has now developed a low resistance cathode plate (ISA Cathode BR™) in response to market demand. The ISA Cathode BR™ provides lower electrical resistance by decreasing the distance the between the end of the copper plating and the solution line.

Plant trials in the Townsville ISA PROCESS refinery and in a major Chilean electrowinning plant were undertaken to prove the performance of the new cathode type BR™. Results to date indicate that significant operating cost savings are available with the use of the ISA Cathode BR™ electrodes.

INTRODUCTION

In 1978 MIM's Townsville Copper Refinery permanently changed the electro-copper industry after the introduction of the permanent stainless steel cathode.

The ISA PROCESS Technology (IPT) allowed for the reduction in manning requirements, provided superior mechanical handling systems, reduced copper inventory levels, permitted a more intense operating regime, improved cathode quality and offered a much safer electrolytic operation. It enabled the commissioning of smaller scale electrowinning operations by making them independent of starter sheet supplies.

The introduction of inherently straight permanent cathodes has necessitated the development of anode casting and preparation systems in conjunction with superior contact arrangements. These developments in combination with the ISA PROCESS have seen the introduction of operating current densities up to 350 A/M^2 and current efficiencies in excess of 98%.

The technology assures the production of better than LME “grade A” quality. The process has been so successful, in this regard, that the LME “grade A” standard, is now considered a minimum by the best producers.

The ISA Cathode BR™ is the latest ISA PROCESS cathode plate offering a low resistance electrode with the potential to reduce power costs significantly. On site trials at Compania Minera Zaldivar supported earlier test work conducted by the ISA PROCESS at Townsville, Australia.

Figure 1: ISA Cathode BR™ in service at Compania Minera Zaldivar

"Lowest resistance cathode"

1.1. The permanent cathode plate

Underlying the success of the process is the basic design of the ISA PROCESS cathode. This design, while constantly being improved over the last twenty years still remains true to the design precepts of I.J.Perry’s original concept (Perry, Jenkins & Okamoto, 1981).

The ISA cathode consists of a 304L stainless steel hanger bar which is stitch welded to a 316L stainless steel blade (3.25mm+ thick). This assembly has been proven so strong that no bond failure has occurred in a commercial operation due to either corrosion or mechanical handling.

The hanger bar assembly is then electroplated with copper to a thickness of 2.5 mm. The 2.5mm of copper provides sufficient electrical conductivity and imparts a degree of corrosion resistance. Under correct operating conditions will provide an operational life without repair in excess of 7 years in electrowinning situations and over 15 years (perhaps as much as 20) in electrorefining situations.

Deterioration of the ISA PROCESS hanger bar system occurs very slowly and is predictable. This permits operators to carefully plan for the refurbishment of their operating cathodes. No catastrophic failures of this assembly have occurred in commercial production facilities.

The diagrams below illustrate a comparison in cathode plate performance over time for the ISA cathode and solid copper hanger bar systems under electrowinning conditions. Zone A illustrates the region where there is no change in performance of the cathode. Zone B is where the performance of the cathode begins to deteriorate. ISA cathodes exposed to corrosive conditions will exhibit this slight drop off in performance. Solid copper bars will experience corrosive attack on the hanger bar to blade joint.

After hanger bar refurbishment the ISA cathode is restored to its original condition and its electrical performance is restored. The solid copper hanger bar will lose electrical performance due to corrosive attack on the joint and sudden failure is possible. The hanger bar must be reattached to the blade. Only "re-welding" of the hanger bar will restore the performance of the cathode. The advantage of the ISA cathode is that there is no sudden failure. A scheduled removal from service can occur and repair of the cathodes can be undertaken. The solid copper bar may experience a limited Zone A as the rate of progression of corrosion of the copper to stainless joint is unpredictable.

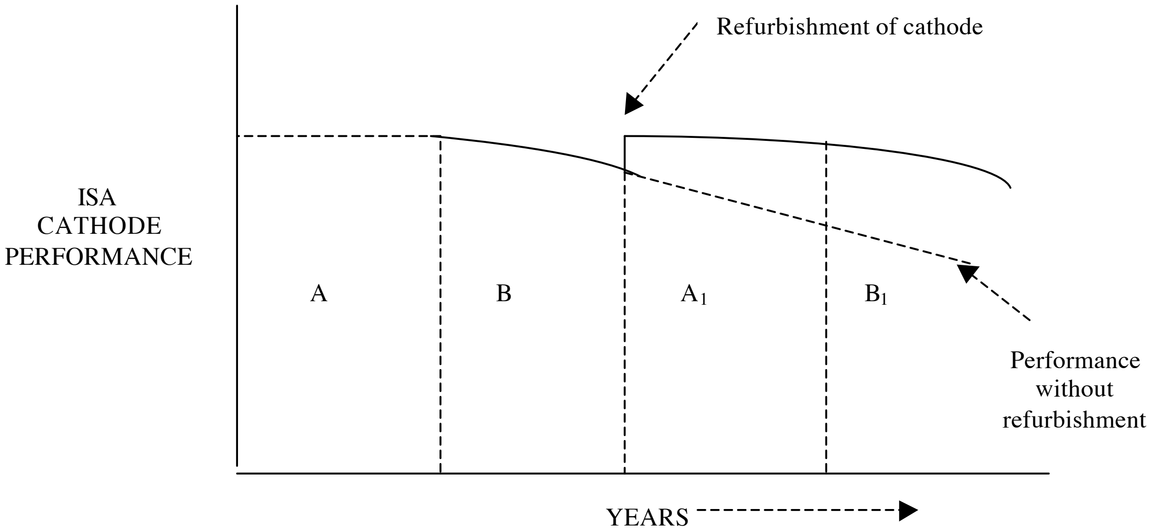

Figure 2: ISA PROCESS cathode performance

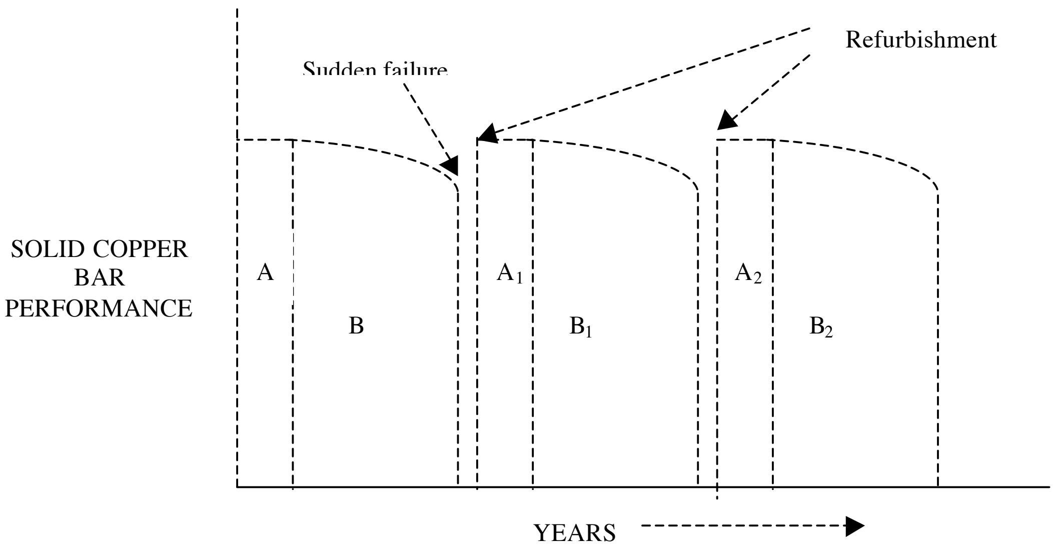

Figure 3: Solid copper hanger bar performance

The assembly of the ISA cathode provides the following key elements:-

- Great mechanical strength
- Inherent straightness, initially and in the long term
- Resistance to annealing (softening) of the hanger bar during the occurrence of electrical shorts
- Sufficient blade thickness to cope with stripping machine stresses, while maintaining the verticality necessary for high current efficiency.
- An edge masking system which is mechanically keyed into the blade.

Since commercialisation, greater than one million ISA PROCESS cathodes have been produced. They have proven to be the most mechanically robust and most corrosion resistant permanent cathode plate on the market. These characteristics are necessary to maintain high current efficiencies in the long term.

1.2.The progression of the permanent ISA cathode plate

The ISA PROCESS cathode has been continuously developed and improved since it was first manufactured in 1978. Figures 4 to 8 illustrate the progression of the ISA PROCESS system.

The first ever ISA Cathode for commercial sale was the I-beam hanger bar illustrated in Figure 4. The copper plating was an average of 1.3mm thick, this was increased to 2.5mm some years later. Prior to this Figure 5 illustrates the rounded bottom I-beam. The design improved the contact pressure and assisted with in cell verticality. The increase in average copper thickness was to improve the corrosion resistance of the hanger bar. Cathode plates with solid copper hanger bars were produced for testing in the Townsville Copper Refinery.

The next development was the move to the rectangular hollow section (RHS) stainless steel bars with a flat top as shown in Figure 6. The RHS bar gave the cathode plate greater rigidity coupled with a much simpler shape to electroplate the copper coating (Armstrong, 2001). The design was modified to a rounded RHS bar shown in figure 7. The rounded top enables a more even distribution of the electroplated copper and ensures any electrolyte will drain off the top of the hanger bar. This reduces the potential for hanger bar corrosion.

The next major development with respect to the cathode plate was the ISA2000 waxless cathode plate. This involved machining a v-groove along the bottom edge of the blade allowing for the separation of the cathode copper into two separate sheets. This eliminated the need for bottom edge wax.

Thinner RHS bars have been used in the manufacture of ISA cathodes based on customers' specific requirements. The latest cathode design, ISA Cathode BR™ is shown in Figure 8. The copper plating has been extended to just above the lifting windows and has an average thickness of 3.0mm

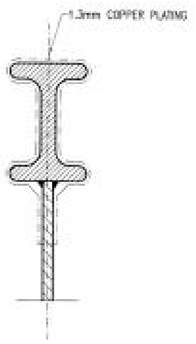

Figure 4

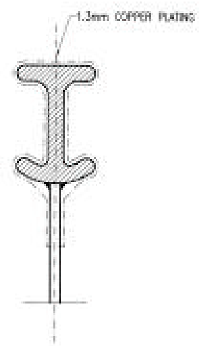

Figure 5

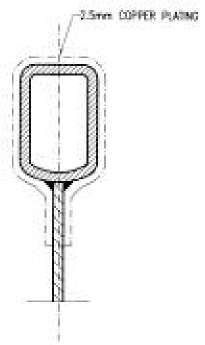

Figure 6

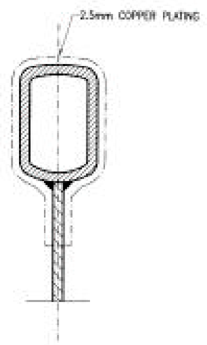

Figure 7

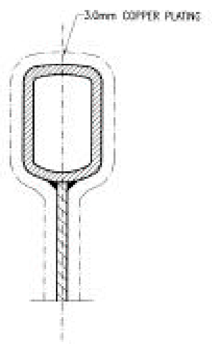

Figure 8

MARKET DEMAND FOR A "LOWER RESISTANCE" CATHODE PLATE

1.3. The earlier ISA cathodes

The earlier ISA cathodes, whilst superior in most aspects had slightly higher resistance than the solid copper hanger bar systems. In spite of the initial higher resistance, the ISA cathode will consume less power per tonne than other cathode types such as the solid copper hanger bar system. While this lower resistance is attractive, the poor long-term performance of the solid copper hanger bar led to its rejection following a large-scale trial at MIM’s Townsville Copper Refinery.

Trials were conducted to compare the performance of solid copper hanger bars and ISA cathodes. Approximately 3000 cathode plates with solid copper hanger bars were manufactured and placed into service for testing. A statistical analysis on a significant proportion of tank house data was carried out. The results indicated that the solid copper hanger bars would produce a lower current efficiency than the ISA cathodes (Bailey, 1995). The difference in current efficiency was 2.4%, with crop 1 results indicating higher inefficiencies of the solid copper hanger bars (Bailey, 1995).

These differences were attributed to actual physical characteristics, such as cathode plate straightness (Bailey, 1995). The ISA cathode plate is inherently straight and maintains its integrity over extended periods of time. Even under severe shorting situations the hanger bar remains straight. This is in direct comparison with the solid copper hanger bar, which is prone to bending.

Trials were also conducted at an ISA PROCESS electrowinning plant to compare ISA cathodes with solid copper hanger bars. These trials supported the results at Townsville's Copper Refinery. They found that the ISA cathodes operated at 2% higher current efficiency than the solid copper hanger bars (4th ISA PROCESS User's Conference 1995 - Iquique).

When considering both current efficiency and conductivity, the ISA cathode plate is the most efficient cathode (Armstrong, 2001).

THE DEVELOPMENT OF THE ISA CATHODE BR™

The standard ISA PROCESS permanent cathode is electroplated with copper to approximately 15 mm down onto the blade. This ensures even flow of current into the blade and a more even initiation of the copper deposit. It was theorised that if this copper was projected further down the blade than the high resistance path through the stainless steel would be significantly reduced and a useful reduction in resistance would occur.

The ISA PROCESS Technology has now developed a low resistance cathode (ISA Cathode BR™). The concept of reducing plate resistance by depositing the copper further was theorised and subsequent calculations highlighted the impact of increasing the depth of the copper plating. An 11 μΩ per plate decrease in resistance with the copper coating down to the windows was calculated. The results showed that the further down the blade the copper coating the greater the potential energy savings.

The BR™ cathode design *differs* from the standard design in two ways:

- The copper plating extends approximately 55mm down the blade compared to 15 - 17mm.
- Increased average copper thickness of 3.0mm compared to 2.5mm.

The *benefits* of this new " high electrical performance cathode" are:

- Extension of the copper plating reduces the amount of electrical resistance that exists between the copper plating and the solution line by reducing the distance the current has to travel through the stainless steel.

- Increasing the thickness of the copper deposit provides greater corrosion resistance, particularly in electrowinning applications where cathodes may be subjected corrosive conditions. (Weston, 2002)

1.4. INITIAL TEST WORK

IPT developed some prototypes of the ISA Cathode BR™. These were tested extensively to determine the electrical characteristics of this cathode plate design. John Nielsen at James Cook University of North Queensland conducted a series of tests relating to this cathode design.

The electrical conductivities of various types of cathode plates were measured. In addition resistive models of the cathode plate were developed to show the electrical losses experienced by each of the cathode types (Nielsen, 2001)

The IPT decided that provided the copper coating does not extend below the lifting windows, no additional restriction would be placed on the operation of the cathodes and on the compatible stripping machines. The concept proved correct and further finite element analysis suggested that compared to a standard cathode, gains as high as 38% could be achieved (Nielsen, 2002). The deeper down the blade the copper coating is deposited the greater the reduction in resistance.

OPERATIONAL TESTING OF THE BR™ CATHODE

Testing of the original cathodes by the ISA PROCESS in the Townsville electrorefinery was commenced and is ongoing. The cathodes have achieved the targeted reduction in resistance while easily fulfilling the operational requirements of the electrorefining process.

A decision was made to extend the testing to electrowinning operations. Following a small test of the BR™ cathode design by a large Chilean electrowinning operation it was agreed to extend the test. Testing of a full cell load of ISA Cathode BR™ electrodes commenced in October 2002.

1.5.Test Data - Compania Minera Zaldivar

A full cell load of trial plates were manufactured to the ISA Cathode BR™ design and placed into service at Compania Minera Zaldivar (CMZ).

Figure 9. Cell load of ISA Cathode BR™ plates on trial at Compania Minera Zaldivar

Figure 10. ISA Cathode BR™ plates on trial at Compania Minera Zaldivar

Since these cathode plates have been in operation their electrical performance has been monitored and the results to date are confirmation of the earlier test work. Current distribution and internal plate resistance measurements have been recorded on a regular basis.

The potential difference between the hanger bar and solution line was measured which enabled the internal plate resistance to be calculated. The results indicate that ISA Cathode BR™ electrodes are a lower resistance cathode plate in comparison with ISA cathodes approximately 7 years old. Figure 11 highlights the difference in performance of the new ISA Cathode BR™ with the older style ISA cathode.

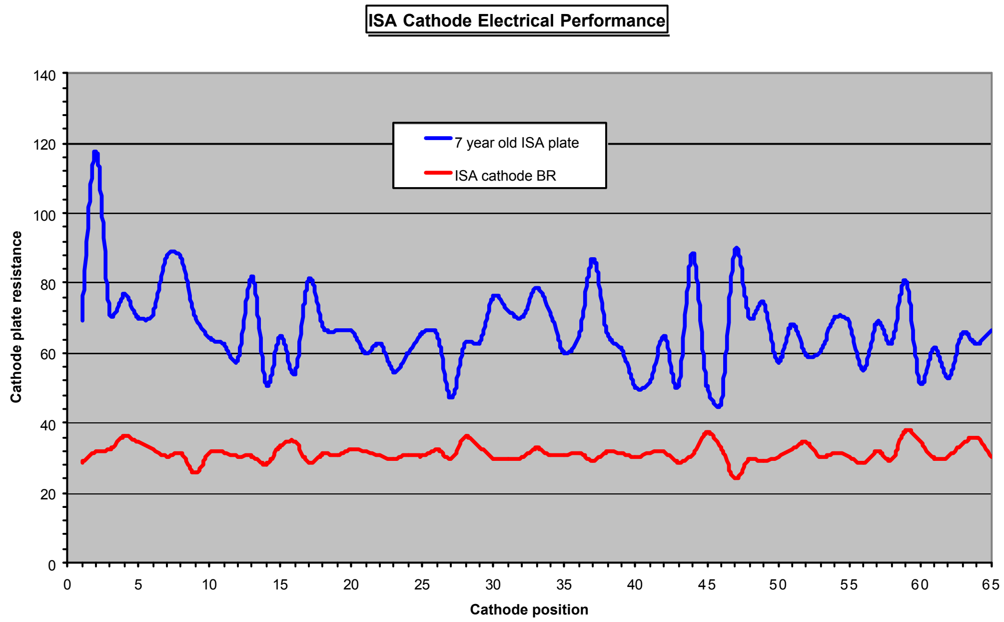

Figure 11: Graph illustrating the difference in cathode plate performance of different cathode types

Further measurements were taken at Compania Minera Zaldivar to compare the performance of a number of cathode plate designs. The results are illustrated in Figure 12. The cathode types that were used in the comparison were as follows:

- ISA Cathode BR™
- Solid copper hanger bars
- Thicker solid copper bars
- Wrapped solid copper hanger bars

Figure 12: Internal resistance of various types of cathode plates

The results from the last set of measurements taken at CMZ on the 8th January 2003 clearly show that the ISA Cathode BR™ electrodes are electrically superior, exhibiting the lowest plate resistance.

POTENTIAL COST SAVINGS

Measurements recorded at Compania Minera Zaldivar illustrate that the ISA Cathode BR™ has the potential to reduce their power costs by approximately US$100,000 per year in a plant of this size. This is the magnitude of saving that the new ISA Cathode BR™ can provide due to their significantly lower plate resistance resulting from the increased depth of copper plating. (Data supplied by C. Pasten, 2002). This is in comparison 7-year-old ISA cathodes and solid copper hanger bars. These measurements were taken on the 15-16th November 2002. A full cell load containing the new ISA Cathode BR™ was measured along with three other standard cells which contained seven-year-old ISA cathodes and solid copper hanger bars.

Calculations showing potential power savings

Potential from contact to solution line	Average difference: 23mV
Average current per cathode plate	660 Amps
Power per cell	989 Watts per cell
Total number of cells in plant	368
Power cost	US$ 0.032 / kWh
Total power savings across the plant	364kW
Total power COST savings per year	US$102,036

Earlier tests and calculations based on data from the Townsville copper refinery also showed that significant cost savings could be made through the application of deeper copper plated hanger bars.

CONCLUSION

The permanent ISA cathode plate has undergone significant changes since its development. The latest development is the ISA Cathode BR™. Past and present test work suggests it is the most efficient cathode plate available, offering significant savings in power costs. The copper plating now extends to just above the bottom edge of the window and the average copper coating thickness has been increased. The ISA Cathode BR™ is a low resistance, mechanically and chemically stable cathode plate.

REFERENCES

Armstrong, W. (27th May - 1st June 2001). Seventh ISA PROCESS Users' Conference, Phoenix Arizona, USA. Session 1. *ISA PROCESS Developments*. MIM.

Bailey, D. (20th July 1995). Internal Memorandum. *Comparison of current efficiencies of CRL solid and RHS hanger bar mother plates*. Copper Refineries Pty. Ltd.

Nielsen.J. (2001- 2002). *Electrical conductivity tests of stainless steel cathode plates*. Report prepared for internal distribution. Series of reports covering tests conducted during the period.

Perry.I.J, Jenkins.J.C, & Okamoto,Y. (23rd Feb 1981). *The use of permanent stainless steel cathode sat Copper Refineries Pty Ltd. Townsville*.

Fourth ISA PROCESS Users' Conference, Iquique - Chile, (3rd -7th April 1995). Session 3, Topic 2 - *Cathode Mother Plate Performance*. MIM Technology Marketing Limited and Lanzco.

Pasten, C. (2002). E-mail correspondence regarding measurements taken at Compania Minera Zaldivar.

Weston, J.L. (14th October 2002). Internal Memorandum. *Summary of plating trials for Zaldivar.* MIBU - Townsville Operation.

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OPERATIONS CONTROL IN XSTRATA TECHNOLOGY TANK HOUSES

C. Phan
Xstrata Technology
Box 5484, Mail Centre
Townsville, Queensland 4810
Australia
cphan@xstratatech.com.au

M. Oellermann
VRT Systems
Level 1/1 Gardner Close, Milton
Brisbane, Queensland 4064
Australia
marko@vrt.com.au

ABSTRACT

This paper outlines opportunities provided for enhanced management and process control by Xstrata Technology (XT). XT has the core advantage of offering the potential for vastly improved electrode handling systems. This fundamental characteristic has enabled XT to develop management and process control systems that are modular, minimalist in their complexity and tailored to a tankhouses operating environment. A review will be presented on the current status of management and process control in XT tankhouses covering the central issue of electrode handling as well as electrolyte circulation systems, voltage monitoring, cathode plate tracking, and product tracking. Particular reference will be made of the recent development by XT and their technology partners, VRT Systems, of a Radio Frequency Identification (RFID) based solution for tracking permanent cathode plates. The system encompasses fixed readers identifying plates passing through the stripping machines, and the use of sophisticated tracking and database software enabling the development of cathode asset management and operational strategies. The performance of individual plates and batches of plates can be tracked through a full service history.

INTRODUCTION

Xstrata Technology (XT) has the core advantage of offering the potential for vastly improved electrode handling systems. This fundamental characteristic has enabled XT to develop management and process control systems that are modular, minimalist in their complexity and tailored to a tankhouses operating environment. This modularity enables control systems to be tailored to the tankhouses operating environment and customer requirements.

TANKHOUSE MANAGEMENT

XT tankhouses deliver high intensity refining, maximum time efficiency and maximum current efficiency via managing and integrating all aspects of the process. Xstrata Technology Tankhouse Management System (XT-TMS) covers:

- Assets
- Energy (i.e. efficiency, etc…)
- Safety & occupational hygiene
- Environment (i.e. green house gases, etc…)
- Costs

PROCESS CONTROL

Within the XT-TMS the central issues of process control require monitoring and control specifically include:

- Electrode handling
  - Cranes
  - Anode preparation
  - Anode scrap washing
  - Cathode stripping
  - Cathode preparation
  - Anode scrap remelting
- Product tracking
  - Bundling
  - Copper cathode
  - Batch labelling
  - Packaging
  - Slimes
- Electrolyte circulation systems
  - Laboratory analysis
  - Online analysers
  - Circulation systems
  - Slimes preparation
  - Reagent management
  - Cell voltage and condition monitoring
  - Auxiliary – boilers, power, steam etc…
- Asset management
  - Cathode plate tracking
  - Maintenance

The XT-TMS centralises control from a single point irrespective of the level of automation. It can provide basic control over general operations or enable sophisticated interlocking control over the entire system encompassing machines and processes. External information from laboratory testing and product sampling is also available to complete the control loop.

Another sophisticated feature is the maintenance of historical records enabling reporting and performance tracking over time, a key feature of the system.

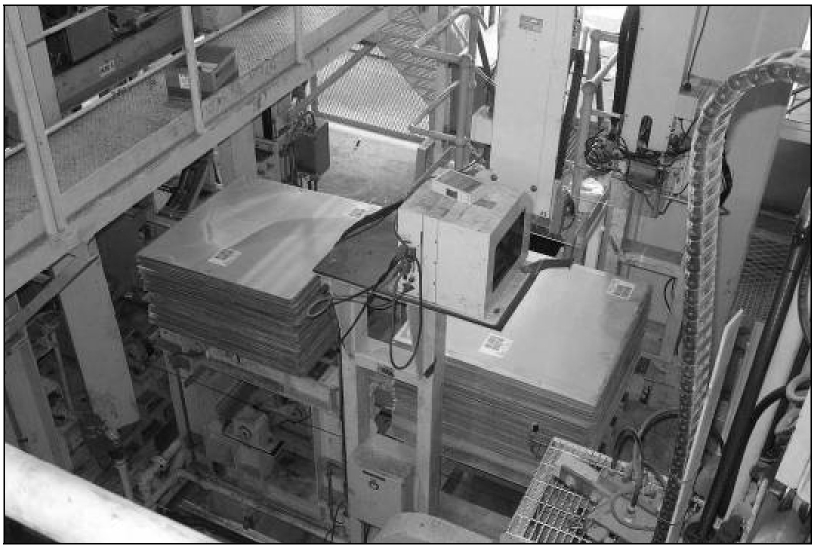

Figure 1 – Copper cathode labelling station

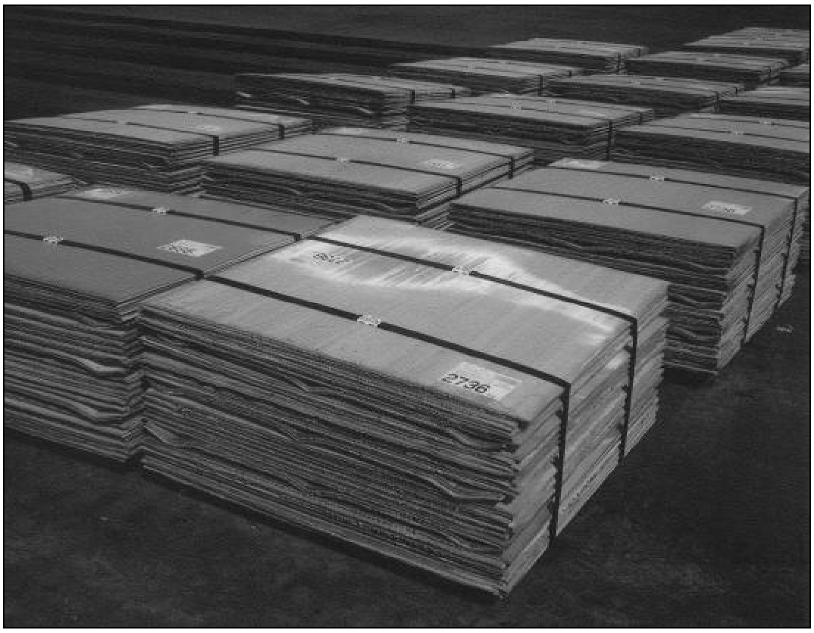

Figure 2 – Copper cathode bundle strapped and labelled

Distributed Control Systems

The Distributed Control System (DCS) monitors and maintains the operational parameters of the tankhouse. It is an automated system that will continue to operate the tankhouse effectively, without human input, while all aspects of the operations are functioning. The DCS is a computerised system that enables operational parameters to be maintained. Changes to the operation parameters, shutdown, start up and monitoring of the refining process can be done from Visual Display Units (VDUs) in the Tankhouse Control Room. Figure 3 shows an example of a graphic screen from a VDU. The DCS is made of three components:

(1) Process Control Unit (PCU),
(2) Distribution Control Unit (DCU), and
(3) Operator Stations (VDUs).

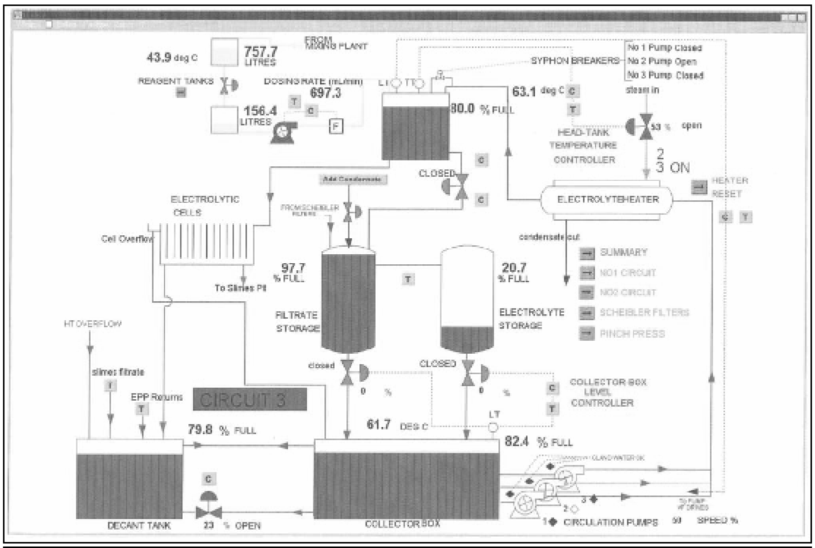

Figure 3 – Graphic screen from a Visual Display Unit

Tankhouse Machines

The major tankhouse machines comprise the Cathode Stripping Machine (CSM), see Figures 4 and 5, Anode Preparation Machine (APM), see Figure 6 and the Anode Scrap Machine (ASM), see Figure 7. Although these machines communicate and operate in line with other tankhouse units such as the overhead crane, their modular setup enables each machine to operate as a stand alone unit without affecting other operating units. Throughput capacities and automation levels for these machines can be designed to suit individual customers.

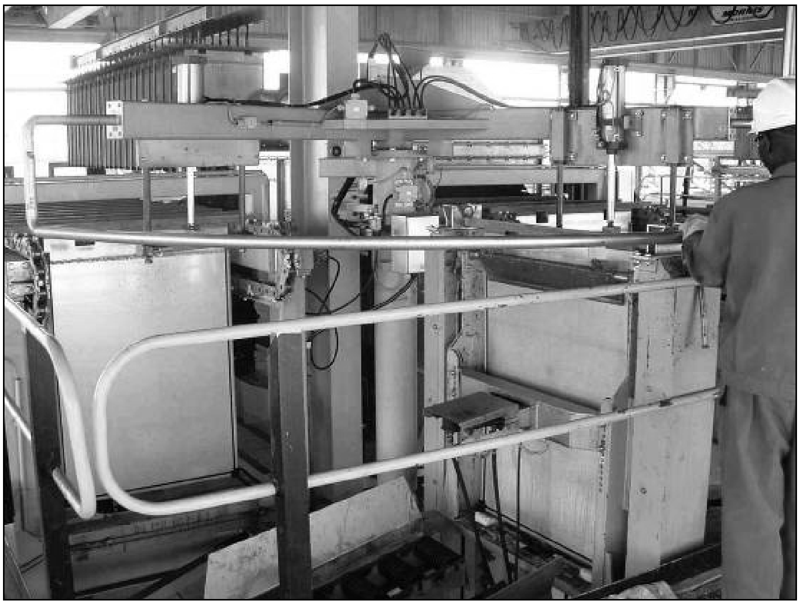

Figure 4 – Low automation Cathode Stripping Machine

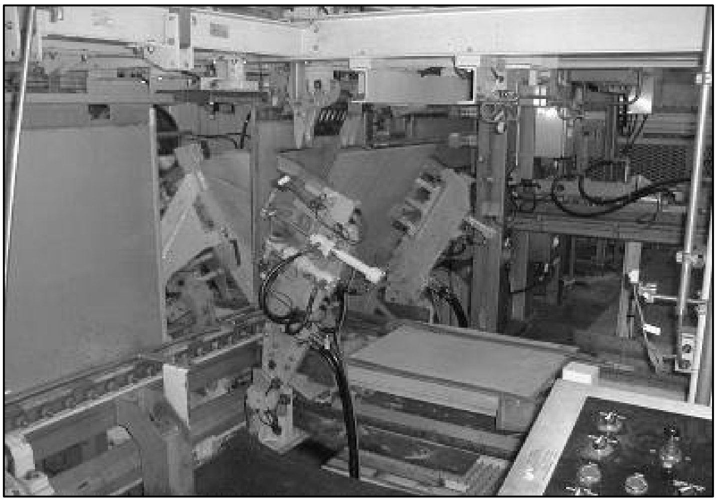

Figure 5 – High automation Cathode Stripping Machine

Figure 6 – Anode Preparation Machine

Figure 7 – Anode Scrap Machine

Tankhouse Overhead Crane

The cranes can be operated in either manual mode or automatic mode. In automatic mode, programs are stored in the crane's DCS and the crane will move automatically to either perform strip operations or strip and scrap operations for the programmed sections. The key function of the overhead crane provides reproducible results with respect to superior electrode handling and alignment. In manual mode, the operator overrides the automatic controls to operate the crane to fix problems encountered during an automatic operation. Manual mode is also used to perform other routine lifting operations in the Tankhouse.

Figure 8 – Tankhouse Overhead Crane

Voltage Monitoring

In order to achieve an efficient refining operation in a tankhouse, it is important to detect all abnormal cell voltages and take corrective action as soon as possible. There are several methods to detect short circuits; these include Gauss and Hall-Effect Meters, multimeters, thermal imaging and computer cell voltage monitoring. These methods can be used individually or in combination with each other. The type of short circuit detection method required is generally dependant on labour cost versus plant capacity, and losses due to current efficiency.

XT offers all the above mentioned methods for shorts detection. The Cell Voltage Monitoring System (CVMS) XT offers is used to measure, record and monitor the voltage across each cell. Each cell voltage is measured and compared against preset limits. If the voltage is out of limits an indication is given. Each CVMS is individually designed to match the specific requirements of the particular tankhouse application and is available as a complete package. Figures 9 and 10 are graphic displays from the XT-TMS extracted from a CVMS showing section and cell voltages.

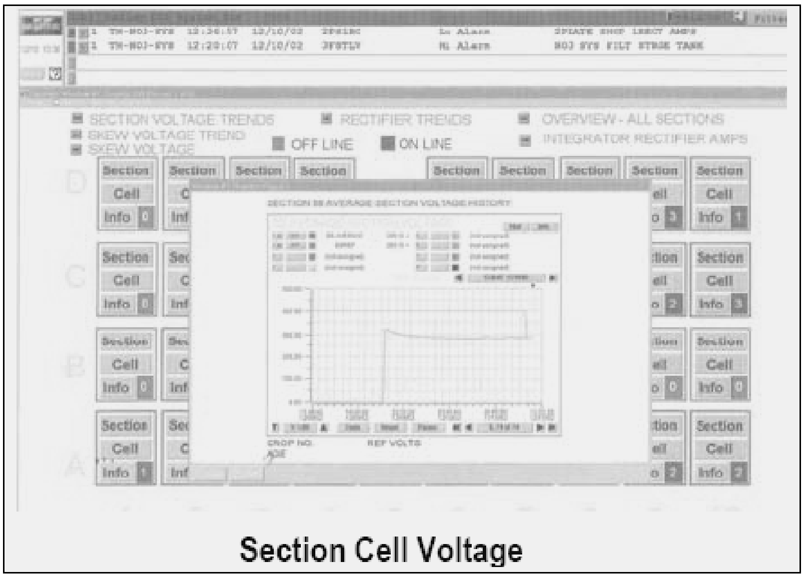

Figure 9 – Graphical display of section cell voltage

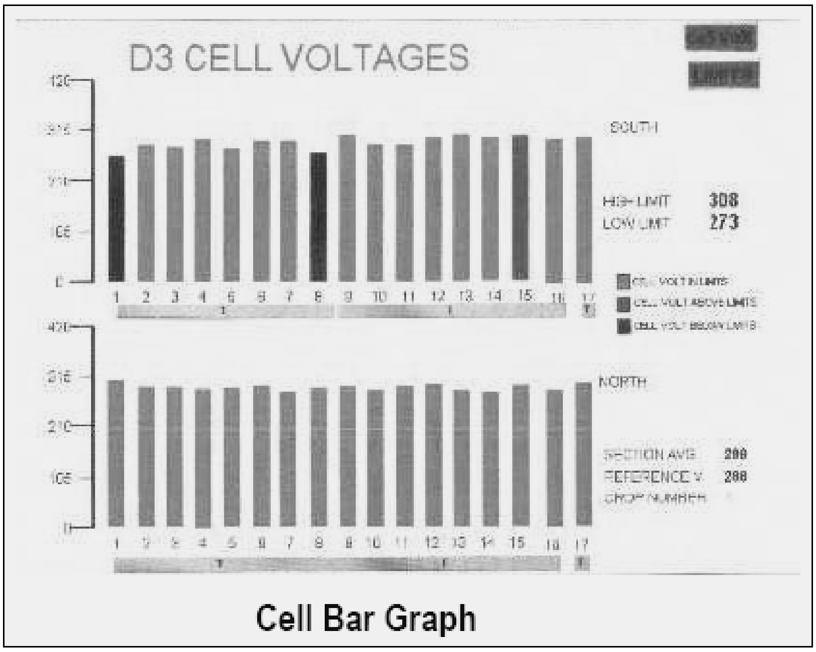

Figure 10 – Bar Graph of section cell voltage

RADIO FREQUENCY IDENTIFICATION (RFID) SYSTEM

Introduction

XT and their technology partners, VRT Systems, have developed an RFID based solution for tracking permanent cathode plates. The system encompasses fixed readers identifying plates passing through the stripping machines and the use of sophisticated tracking and database software enabling the development of cathode asset management and improved operational control strategies, see Figure 11. The performance of individual plates and batches of plates can be tracked through a full service history.

Some of the opportunities that have been identified are:

- Tracking current efficiencies for individual and groups of cathode plates.
- Tracking weights of individual cathodes with significant implications for improvements in tankhouse operations.
- Tracking edge strip performance and failure rates.
- Tracking cathode quality by means of cathode to anode positioning (in EW operations where anodes are fixed).
- Distinguishing between old and new plates.
- Tracking cathode plate performance in segregated circuits.
- Tracking cathodes plates requiring the use of plate repair facilities.

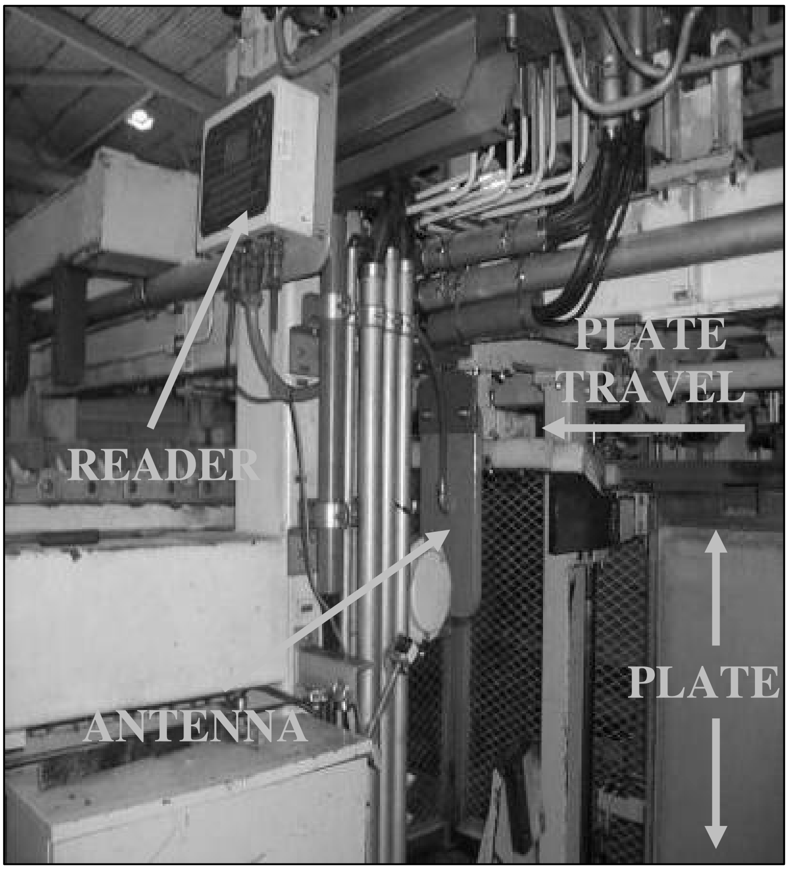

Figure 11 – RFID reader mounted to a Cathode Stripping Machine

Development Phases / Methodology

The extreme operating environment resulted in a focus to date on resolving the issues around reliability of hardware associated with readers, tags and tag housings.

Early development work has centred on configuration of the readers to ensure that all necessary data is captured. Positioning of the readers on the Cathode Stripping Machine (CSM) will be dependant on individual layout/setup of the machine. The aim is to achieve a closed loop system such that every individual cathode plate can be traced to a particular location.

Ideally there would be one reader on the inlet of the machine to read every plate that passes through the CSM, one reader to capture the plate once it has been stripped and transferred by the transfer conveyor and ready to go back into the tankhouse, one reader on the reject conveyor to capture all plates that are rejected for any particular reason, such as damaged edge strips or sticky copper.

New plates or repaired plates that are returning to the tankhouse need to be read before going into service. This can either be done by feeding the plates through the CSM (which is required if it is a bottom wax operation), or the plates can be read using another fixed or handheld reader and the information transferred onto the database.

Various tag designs with respect to tag housing material and tag profile have been trialled to determine the most suitable design. The tag housing most suitable will be one that fits the following criteria: ease of fitting to the cathode plate, material suitability to handle the corrosive and harsh tankhouse environment, and longevity of tag life.

Tag Position on Plate

Environments with high levels of metal pose specific challenges for RFID implementation and generally require special metal-capable RFID tags. Metal-capable RFID transponders usually rely on a surface field-effect to operate and have specific mounting position and orientation requirements to achieve sufficient read reliability. In contrast, the RFID solution developed by XT and VRT allows tags to be mounted in a hole punched in the plate, enabling a single tag to be scanned from either side of the plate. Additionally this reduces the overall tag profile and provides maximum flexibility in tag placement on the plate surface.

XT has identified several locations on the cathode plate to insert the tag. Location will be dependant on individual layout of the CSM. Tags can either be fitted to the centre of the plate just below the copper plating extended from the hanger bar (this is the ideal position, however, this may not suit all CSM layouts), see Figure 12. The position of the tag can be modified to suit both the CSM layout and cathode plate configuration of individual customers.

Since the plates operate in a closed system and no data needs to be stored on the actual tags, a read-only tag inlay has been selected. These have a guaranteed globally-unique 16 digit number which is assigned at time of manufacture. The tag inlays are mounted in a protective housing specifically designed for the conditions found in acidic electrolytic processes.

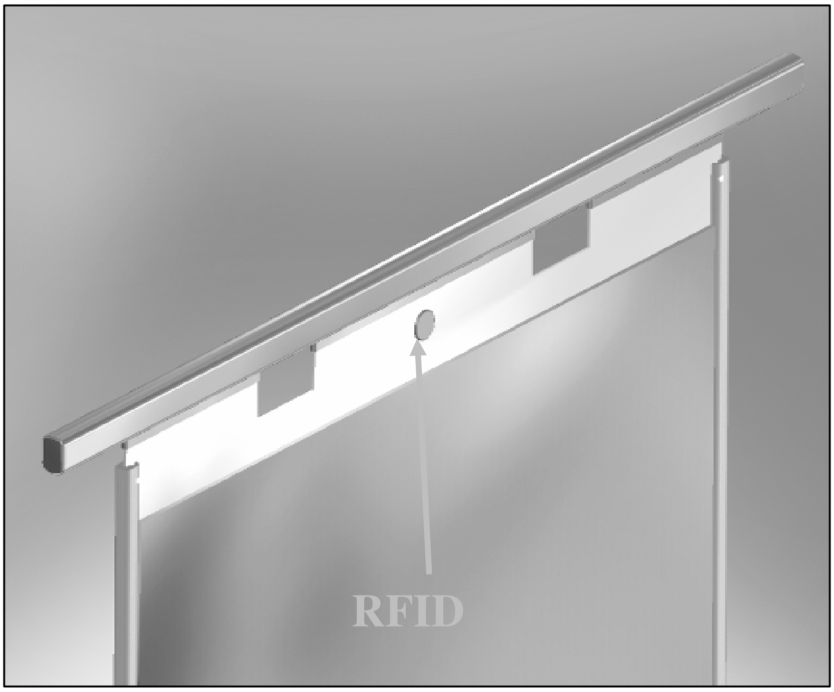

Figure 12 – Schematic of RFID tag positioned on stainless steel cathode plate

The System

The RFID readers and tags form part of a broader plate tracking and asset management system under development by XT. The system comprises RFID tags and readers, coupled with a controller running Plate Asset Management Software to provide a complete tracking and asset management solution. The system is intended to offer asset owners the means to analyse plate performance through life, identify and locate problematic or under-performing plates, determine the optimal end-of-life time for plate batches, and trace plates through offsite or contracted maintenance.

Tracking Functionality

The plate tracking system incorporates a number of key capabilities:

- Identity Preservation – Fundamental to whole-of-life tracking is the preservation of plate identity. The system separates the plate ID from its RFID tag so that tags can be replaced and the tracking system retains a consistent plate identity (serial number) for analysis purposes.
- State Tracking – The system can be configured to record plates in any number of states, (e.g. “in service”, “stripping”, “rejected – awaiting repair”, “quarantined”, “in repair”, “awaiting return to service” and so on). This enables analysis of duty cycles and overall asset utilisation.
- Location Tracking – The system tracks individually identified plates through any number of discrete logical locations. The locations are configurable to support various tank house capacities and layouts, and other on-site and off-site maintenance locations, including mobile locations such as vehicles. Locations are defined in a hierarchy and can be configured to the resolution required – for example: site/tank-house/section/cell, or site/area/workshop.

- Plate Grouping – As plants use plates of various ages (and sometimes of slightly different types as improvements to plate design are made), it is beneficial to compare plates with similar age or type. The system tracks plates by plate batch/group, so that queries and analysis can be performed by each batch of plates within a plant.

Additional Data Capture

RFID readers and tags provide essential data for tracking of plates through the system, but can only reveal limited statistics surrounding cycle times and failure rates. In order to provide further value, the plate tracking system is designed to allow additional qualitative data to be captured along with associated key process elements:

- Plate characteristics: manufacture date, batch number, material thickness, edge strip type etc.
- Cell conditions: profile of electricity consumption, electrolyte details etc.
- Plate transfer details (e.g. removal of plate from cell): weight of copper (when removed at stripping machine).
- Inspection and maintenance details: Reason for rejection, maintenance carried out etc.

The capture of this data is enabled by providing interfaces to external data capture systems:

- Facilities for interfacing to a range of PLC, DCS and instrumentation systems via optional embedded supervisory control and data acquisition (SCADA) software. This provides opportunities for interfacing to automated and semi-automated crane handling systems to provide cell-level plate tracking in the tank house.
- Screen based manual input (console and web browser based).
- Interfaces to wired and wireless field devices (PDA and mobile RFID scanners) for plate inspection and maintenance activities.

Equipment

The RFID readers are purpose-built industrially hardened, sealed units with onboard data logger, onboard keyboard and screen, and a serial interface to the tracking system. The units support a read range of 200mm, read speed of 70 milliseconds, and operating temperature range of -30 °C to 70 °C.

Additional handheld RFID scanners are being used for manual plate scanning, for survey and pilot system verification. These are battery-operated units designed for the tank-house environment and all-weather outdoor use (-30 °C to 70 °C). They can support RF wireless, cable or blue-tooth connectivity.

Xstrata Copper – Townsville Operations Configuration

The current development system is operating on two stripping machines; each fitted with fixed RFID readers on the CSM inlet and reject ports. The tracking software infers plates returned to the tank-house (those scanned on the inlet port, but not rejected).

The plate tracking software is currently running on an industrial PC server, connected to the fixed RFID scanners via serial line drivers.

Performance

The RFID readers are modified from existing industrial process application, so are already field-proven in harsh environments. The RFID tag inlays have proven reliable and read rates in the current configuration are high for an RFID application of this type.

The current RFID tag housing under trial is a single-piece "snap-in" polymer design that does not require adhesive or fasteners to affix to the plate. There have been some issues with material deformation causing a small number of tags to come away from the plate. This is due to in-process degradation of the polymer used to manufacture the prototype units, however, other materials with known resilience in a tank-house environment are now being tested. Further developments underway may see the configuration of the tag housing change.

The plate tracking and asset management software is still being refined, but has proven to be stable and reliable.

The read reliability of the system is exceptional with a readability of 99.95% to date. It is believed this a significant improvement on other systems currently available on the market with quoted accuracies of >95%, [1].

Development

The most price-sensitive component in the plate asset management system is the RFID tag, and is consequently an area of continuing development and refinement. Improved tag housing designs and materials are being tested, with the goal of minimising installed cost, while at the same time maximising tag longevity.

The plate asset management software is being refined and tailored to suit the requirements for plate asset management and process improvement in XT tankhouses. This will likely be an area of ongoing development as further opportunities for improvement are identified.

Further development work is being undertaken to improve the system packaging. The system may be available as a server based solution, but efforts are being considered to package the tracking engine software in a rugged appliance-based form factor:

- Suitable for rack or DIN-rail mounting in electrical control cabinets.
- Ethernet connectivity, removable non-volatile memory card for configuration storage, network backup and/or remote database.
- Zero- or minimal- configuration to set up – allow tracking engine to be swapped out by field staff for easy maintenance and repair.
- Web browser based user interface for configuration and operation.
- Facilities for Open Database Connectivity (ODBC) for ad-hoc analysis and reporting capabilities. Acknowledgments

CONCLUSIONS

Xstrata Technology has developed management and process control systems that are modular, minimalist in their complexity and tailored to a tankhouses operating environment. XT offers a complete tankhouse management system with respect to electrode handling as well as electrolyte circulation systems, voltage monitoring, cathode plate tracking, and product tracking.

Developments by Xstrata Technology and their technology partners, VRT Systems, of an RFID based solution for tracking permanent cathode plates have proven to be highly successful. The read reliability of the system is exceptional with a readability of 99.95% offering a significant improvement on other systems currently available on the market.

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The authors would like to thank Xstrata Technology for allowing them the time and resources to undertake this work and publish this paper. Special thanks to the Xstrata Copper Refinery in Townville for allowing the trials to be perform in their tankhouse. This project has had input and assistance from a number of people at Xstrata Copper not least of which is Noel Kimlin, Les Brand, Bruce Hall and Peter Hall as well as Kellie Eastwood and Tony Ruddell from the Xstrata Technology development team.

REFERENCES

1. CSC, http://www.csc.com/solutions/supplychainmanagement/casestudies/2213.shtml sited 20 December 2006.

2. F. Westlake, L. Brand and B. Jenkins, “Shorts Detection and Correct”, Xstrata Copper Training Package TRA-641101, Townsville Operations, Queensland, Australia, 2003.

3. L. Law and D. Fowles, “Distributed Control Systems”, Xstrata Copper Training Package TRA-641003, Townsville Operations, Queensland, Australia, 2003.

4. F. Westlake, G. Lynch and P. Clifford, “Cathode Stripping Machine”, Xstrata Copper Training Package TRA-638301, Townsville Operations, Queensland, Australia, 2003.

5. F. Westlake, D. Robertson, P. Cutts and P. Kopittke, “Kunz Crane Operations”, Xstrata Copper Training Package TRA-638101, Townsville Operations, Queensland, Australia, 2006.

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Statistical analysis of the effect of operating parameters on acid mist generation in copper electrowinning

Reza Al Shakarji [a], Yinghe He [a,*], Simon Gregory [b]

[a] School of Engineering and Physical Science, James Cook University, QLD 4811, Townsville, Australia
[b] Xstrata Technology, Copper Refinery Limited, Hunter St, QLD 4811, Townsville, Australia

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ABSTRACT

Acid mist is generated during the final stage of hydrometallurgical metal refining processes including the electrowinning of copper. In this study, the effect of five process parameters and their interactions on the amount of acid mist generated is analysed quantitatively. The amount of acid mist generated was measured under 32 different operating conditions. It was found that solution's temperature and mist suppressant chemical FC-1100 had significant effect on the amount of acid mist generated. More than 90% of the variations in the acid mist generation can be explained by changes in these two parameters and their interaction. To a lesser extent, electrical current density and solution acidity also affected the total amount of acid mist generated. The anode's age and most of the 3, 4, and 5-way parameter interactions were found to have negligible influence on the amount of acid mist. Overall, acid mist was found to increase with temperature and current density. In contrast, increasing the viscosity of the solutions tends to decrease the amount of acid mist.

1. Introduction

Electrowinning is an electrochemical process that is used to extract metal from its solution, and is extensively used in the production of copper. More than 20% of the world's primary copper is produced through electrowinning (Davenport et al., 2002).

In the electrowinning of copper, a direct electrical current is passed between an anode and a cathode that are submersed in a copper-rich solution (Robinson et al., 1994). At the inert anode, water molecules are electrolysed and oxygen bubbles are formed on the surface of the anode. These oxygen bubbles grow and eventually detach from the surface and rise in the bulk of the solution. These bubbles burst at the free surface of the solution and produce highly acidic droplets; of which the fine ones become airborne and form an acid mist throughout the tankhouse of the electrowinning plant.

Acid mist is highly corrosive and results in the corrosion of cathode plates, anode's hanger bar, tankhouse equipment and building structures. Acid mist also poses a serious health hazard and causes extreme discomfort to the skin, eyes and respiratory systems of the tankhouse workers (HSIS, 2009). The Occupational Safety and Health Administration (OSHA) recommends a time-weighted average (TWA) exposure limit of 1 mg of sulphuric acid per m^3 of air, and a short term exposure limit (STEL) of 3 mg m^{-3} (OSHA, 2003).

There have been many attempts to eliminate or minimize acid mist in copper electrowinning operations (Mella et al., 2006). Polyethylene balls, suction hoods, mats, brushes and wipers, chemical reagents and forced ventilation are examples of such attempts (3M, 2007; Davis and Eng, 2002; Hooper, 2008; Mella et al., 2006; Sunwest, 2004). Qualitatively, the use of chemical reagents such as FC-1100, Mistop, Dowfroth, and alkylated ethoxylates has been rated as the most effective method of suppressing acid mist (Bender, 2010). However, there have been no systematic studies to quantitatively compare the effect of different operating parameters, including the use of a chemical reagent, on the amount of acid mist generated. Most of the published works to date, have only examined the effect of one or two parameters individually without considering any possible interaction effects on the amount of acid mist (Alfantazi and Dreisinger, 2003; Cheng et al., 2004; Hosny, 1993; San Martin et al., 2005a,b; Sigley et al., 2003).

This paper examines, quantitatively, the relationship between the amount of acid mist generated and five operating parameters. These parameters are the age of the anode, electrical current density, solution temperature, sulphuric acid concentration of the solution, and the presence of a typical chemical mist suppressant (i.e. FC-1100). The results are useful for the design of more efficient methods or systems for acid mist minimization at electrowinning tankhouses.

* Corresponding author. Tel.: +61 7 47814270; fax: +61 7 47816788.
E-mail address: yinghe.he@jcu.edu.au (Y. He).

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2. Methodology

2.1. Equipment set up

The copper electrowinning process was replicated in a bench-scale cell. This cell (C2 in Fig. 1) was constructed of 10 mm thick clear acrylic and had a capacity of 6 L. During each test, electrochemical reactions resulted in continuous copper depletion and acid generation in the solution. Therefore, a peristaltic pump was utilized for gradual and continuous addition of fresh solution, from C1 container to C2, to maintain consistency in the composition of the solution. A horizontal slit in the side of C2 was utilized to keep the level of the solution in the container constant.

Four submersed heaters were placed in the corners of C2 to keep the solution at a constant temperature for the duration of each test. To replicate industrial operations, Pb–Ca–Sn alloy and 316 L stainless steel were used as anode and cathode, respectively (Houlachi et al., 2007). For each set of experiments a fresh batch of solution was synthesized that contained 45 g L^{-1} Cu, 15 mg L^{-1} Guar gum, 20 ppm Cl and 100 ppm Co. The synthesized solution was similar to the electrolyte solutions found in most copper electrowinning tankhouses worldwide (Robinson et al., 1994). The sulphuric acid concentration in the solution, however, was one of the five selected variables and its concentration differed from that of a typical copper electrolyte solution.

Nitro cellulose filters were used to capture acid mist. These filters were 47 mm in diameter and had a pore size of 0.45 μm which ensured the capture of very fine acidic droplets. For each experiment, a fresh filter paper was installed at 45 mm above the free surface of the electrolyte solution inside the electrowinning cell (C2). The filter was held by an inverted funnel (F in Fig. 1) and connected to a vacuum pump (VP) via a pneumatic tube. For precise air flow measurements, the drawn air was dehumidified by passing it through an enclosed flask that contained silica beans (D). A flow meter (FM) with a built in valve was installed on the pneumatic tube to ensure a constant air flow of 5 L min^{-1} through the filter for the duration of each experiment.

At the end of each test, the used nitro cellulose filter was removed from the cell and placed in 25 mL of deionized water and stirred for about 60 min. The pH of the solution was then measured and the amount of the captured acid was calculated as grams of sulphuric acid per cubic meter of air drawn through the filter.

2.2. Experimental design

The main goal of the present work was to compare, quantitatively, the effect of different operating parameters on the amount of acid mist generated during a typical copper electrowinning process. To fully explore the main effect of each individual parameter as well as any possible interaction effects, the 2 K factorial method was utilized to determine the required experimental conditions (Montgomery, 2005). In this method, the examined parameters are tested at two levels (low and high). The bigger the difference between the low and high levels of a parameter, the more reliable its effect measurements would be (Montgomery, 2005). Table 1 illustrates the examined parameters and their low and high level values.

The values shown in Table 1 were selected so that the midpoint between low and high levels of each parameter represented the typical value used in most copper electrowinning tankhouses (Houlachi et al., 2007). For example, the temperature of the electrolyte solution is usually kept at about 45 °C. Thus, the low and high limits of temperature for the experiments were set at 30 °C and 60 °C, respectively.

Based on the 2 K factorial method, 32 parameter combinations were required to fully examine the effect of five parameters at two levels. For reliable data analysis, a minimum of two replicates were needed for each test condition. Hence, 64 tests were conducted to determine the influence of each parameter on the generation of acid mist and also to identify any significant interactions amongst the selected parameters.

3. Results and discussion

3.1. Descriptive statistical analysis

In all the 64 experiments at 32 different operating conditions, the least amounts of detected acid mist were 0.03 and 0.02 mg acid m^{-3} air. These two tests were repeats, conducted with an old anode at low current density in a solution with low acidity, low temperature and high concentration of FC-1100.

The highest amounts of detected acid mist were 114.4 and 117.1 mg acid m^{-3} air. These two repeats were conducted with a new anode at high current density in a solution with low acidity, high temperature and no FC-1100.

The test results proved to be highly repeatable. The average relative error between the repeats of medium–high acid mist concentration tests was 18%. The smallest relative error was 0.001%. For the very low acid mist concentration tests, however, the average relative error between the repeats was 41%. This high relative error was essentially due to the resolution limit of the measurement method.

To distinguish the effect of individual parameters, the average amount of collected acid mist for each level of a parameter was calculated. The bar graph in Fig. 2 illustrates the results where each bar represents the average amount of acid mist collected from 32 independent experiments.

In Fig. 2, it can be seen that highest amounts of acid mist were generated when the solution was kept at high temperature or when no FC-1100 was added to the electrolyte solution. To a lesser extent,

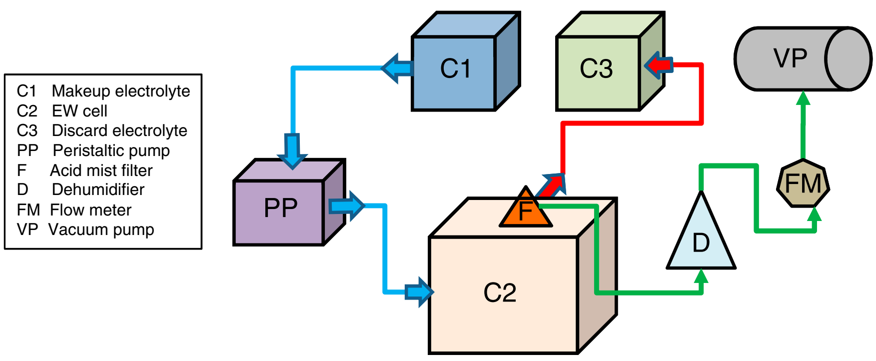

Fig. 1. A schematic view of equipment setup.

Table 1
The selected test variables and their values.

No	Examined parameter	Low	High
1	Anode age (months)	0	6
2	Current density (A m^{-2})	200	400
3	Temperature (°C)	30	60
4	Acidity (g L^{-1})	100	250
5	FC-1100 (ppm)	0	30

high current density, low sulphuric acid concentration in the solution and new anode also favoured higher acid mist generations.

High temperature solutions produced the most amounts of acid mist. Temperature is known to affect the rheological properties of fluids. Surface tension and viscosity of the electrolyte solution were known to strongly influence the final size and the burst process of the oxygen bubbles (Xie et al., 2009; Xu et al., 2009). Thus, to find an explanation for the strong influence of temperature on acid mist, the effects of temperature on both the surface tension and the viscosity of the solution were evaluated and the results are discussed in detail in Section 3.3.

The second highest amount of acid mist belonged to the tests where no FC-1100 was added to the solution. The addition of 30 ppm of FC-1100 reduced the acid mist amount from 47.2 to 7.3 mg acid m^{-3} air. As will be seen later, this reduction in the amount of acid mist in the presence of FC-1100 is believed to be caused by a change in the burst mechanism of bubbles at the free surface of the solution through changes in the surface viscosity and surface elasticity.

The third highest acid mist concentration belonged to high current density experiments. Based on Faraday's law, electrical current is directly related to the rate of chemical reactions that occur during an electrochemical process (Harris, 2007). Decomposition of water molecules at the surface of the anode is the main anodic reaction that takes place during the copper electrowinning process. Therefore, based on Faraday's law, doubling the electrical current density will double the total volume of the generated oxygen bubbles.

Our previous experimental work suggested that changing the electrical current density had negligible effect on the final sizes of the bubbles that detached from the anode (Al Shakarji et al., 2010). Consequently, doubling the current density will approximately double the number of oxygen bubbles generated. This increase in the number of bubbles (per unit time) with current density results in a net increase in the number of bubbles that burst at the free surface of the solution which in turn produces a higher number of airborne acidic droplets (i.e. acid mist) per unit time per unit surface area of the solution.

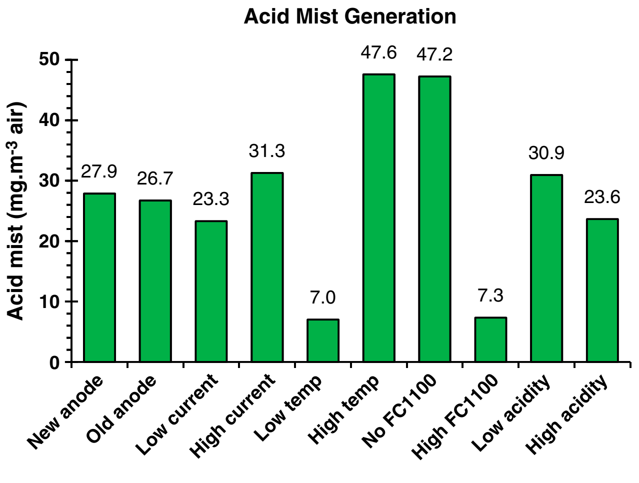

Fig. 2. Mean acid mist generation at different operating conditions.

3.2. Quantitative statistical analysis of test parameters on acid mist generation

A 5-way ANOVA analysis was conducted on the raw experimental data to determine the full effect of test parameters on the amount of acid mist generated. This analysis returned p values less than 0.05 (i.e. significant at 95% level) for 18 of the 32 possible parameter combinations. Cohen classifies the magnitude of a parameter's effect into three categories of small, medium and large (Cohen, 1988). These categories correspond to R^2 values of 0.01, 0.09 and 0.25, hence accounting for 1%, 9% and 25% of the total variance, respectively (Cohen, 1988). To quantify the influence of the aforementioned 18 conditions on acid mist generation, the R^2 value was calculated for each case based on its Pearson's r value (Field, 2005). The top ten cases (with respect to R^2) are shown in descending order in Fig. 3.

The quantitative analysis (Fig. 3) shows that temperature, FC-1100 and the interaction of these two parameters are the most influential parameters in determining the amount of acid mist generated. To a lesser degree, current density and solution acidity also affected the generation of acid mist. Anode's age with an R^2 value of 8×10^{-5} was determined to be a parameter with negligible effect on the amount of acid mist generated.

The ANOVA analysis returned an overall adjusted R^2 value of 0.986, which meant 98.6% of the variation in acid mist recorded in the series of experiments could be explained by changes in the five parameters. The uncontrolled variables and instrumentation errors accounted for only 1.4% of the measured acid mist variations which implied the experiments were conducted at a highly controlled environment.

The influence of individual test parameters as well as that of important interactions (shown in Fig. 3) on acid mist is discussed in more details in the following sections.

3.2.1. Effect of temperature and FC-1100 on acid mist

Based on Cohen's classification, both temperature (T) and FC-1100 (S) parameters with R^2 values of 0.378 and 0.366, respectively, proved to have large effects on the amount of acid mist generated. The interaction of these two influential parameters (T*S) with an R^2 value of 0.159 had a medium effect on acid mist. These effects can be seen graphically in Fig. 4.

Fig. 4 also shows that the presence of FC-1100 in the electrolyte solution strongly influenced the effect of temperature on the amount of acid mist generated. In the absence of FC-1100, a 30 °C increase in the solution temperature increased the amount of acid mist by almost 67 mg m^{-3} of air whereas in the presence of FC-1100 the same increase in the solution temperature resulted in only 14.3 mg more acid mist per m^3 of air.

The vast difference in the slopes of the two lines in Fig. 4 indicated the strong interaction between temperature and FC-1100. The T*S interaction alone accounted for nearly 16% of the variations seen in the amount of acid mist generated. Overall, temperature (T), FC-1100 (S), and T*S have a combined R^2 value of 0.903 which means that

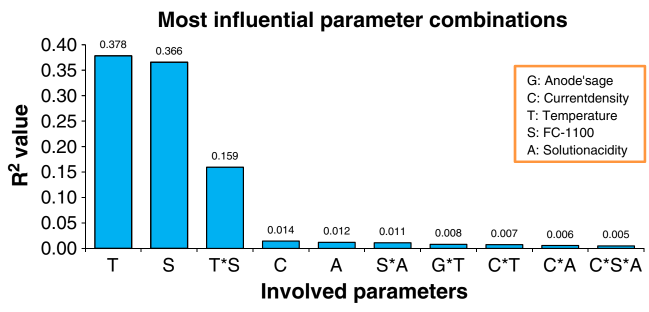

Fig. 3. Quantified influence of different parameters and parameter combinations on the amount of acid mist generated.

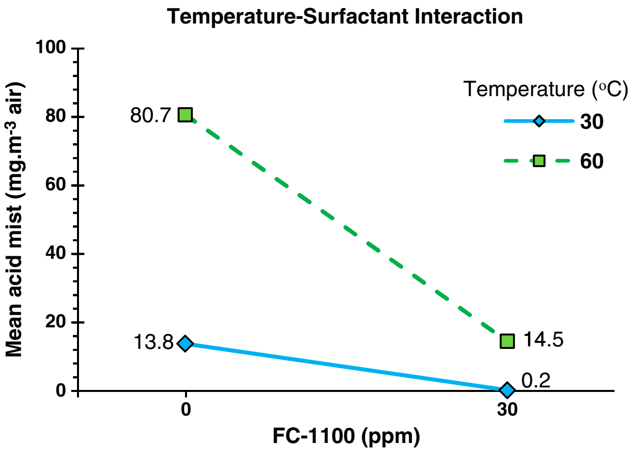

Fig. 4. The temperature–FC-1100 interaction based on mean acid mist values.

changes made in these three parameters are sufficient to explain more than 90% of the variations seen in the amount of acid mist generated.

3.2.2. Effect of current density on acid mist

Current density with an R^2 value of 0.014 was the fourth influential parameter in the amount of acid mist generated. In absolute terms, the effect of current density on acid mist is much less than that of temperature and FC-1100 and based on Cohen's classification the effect of current density is considered small. Nevertheless, in relative terms, current density is an important factor as the amount of acid mist generated at 400 A m^{-2} was 34% more than that generated at 200 A m^{-2} (Fig. 2).

To compare the magnitude that current density and FC-1100 affect the amount of acid mist generated, the averaged acid mist measurements were plotted at different current densities with or without the presence of FC-1100. The results are shown in Fig. 5.

Fig. 5 confirms again a substantial reduction in acid mist at both low and high current densities when FC-1100 is added to the electrolyte solution. Since there is no significant difference in the slope of the two lines in Fig. 5, it means that current density has no significant influence on the effect of FC-1100 on acid mist generation, i.e. little interaction effect between the current density and FC-1100.

Fig. 5 also shows that, regardless of the presence of FC-1100, an increase in current density increases the amount of acid mist generated. However, the acid amount did not double when the current density was doubled. This is because acid mist is produced from the burst of bubbles that ejects droplets into the air of which some become airborne. The amount of mist generated from the simultaneous bursts of two neighbouring bubbles is known to be less than the sum of mist amount from the bursts of two individual bubbles separately, due to interferences between the bursts of the bubbles. At a higher current density, the likelihood for a number of neighbouring bubbles to burst simultaneously is higher. Consequently, even though the number of oxygen bubbles must be doubled when the current density is doubled, based on Faraday's Law and that the bubble size does not change with current density, the acid mist amount is expected to be less than double.

3.2.3. Effect of solution acidity on acid mist

The ANOVA analysis returned an R^2 value of 0.012 for the solution acidity which meant this parameter was the fifth most influential parameter in acid mist generation, which is comparable to that of the current density (0.012 vs 0.014). This means that the acidity of the solution is approximately as influential as the current density in acid mist generation.

The C*A interaction is listed as one of the top ten influential parameters (Fig. 3). This interaction is confirmed from the considerable difference in the slope of the two lines shown in Fig. 6. For high acidity solutions, doubling the current density from 200 to 400 A m^{-2} only resulted in 13% increase (equivalent to 0.087 standard deviations) in the amount of acid mist. In contrast, doubling the current density in low acidity solutions resulted in a staggering 54% increase (equivalent to 0.395 standard deviations) in the amount of acid mist.

Fig. 7 shows the effects of solution temperature and acidity on the acid mist amount. It again confirms the profound effect that temperature has. Further, the two lines in Fig. 7 have similar slopes (1.46 for low acidity solutions and 1.24 for high acidity solutions), which suggests that the interaction between temperature and acidity is negligible.

The plots in both Figs. 6 and 7 reveal an interesting phenomenon that low acidity solutions consistently resulted in higher amount of acid mist than high acidity solutions did, regardless of the applied current density and temperature. This apparent counter-intuitive result will be explained in detail in Section 3.3 below.

3.3. The role of surface tension and viscosity in acid mist generation

The previous two sections presented statistical observations on the influence of operational variables and their interactions on the amount of acid mist generated. This section offers mechanistic explanations to the results obtained in this investigation.

3.3.1. Effect of surface tension

Qualitatively, temperature and FC-1100 are both known to affect the surface tension of a solution. To quantify their effect on the

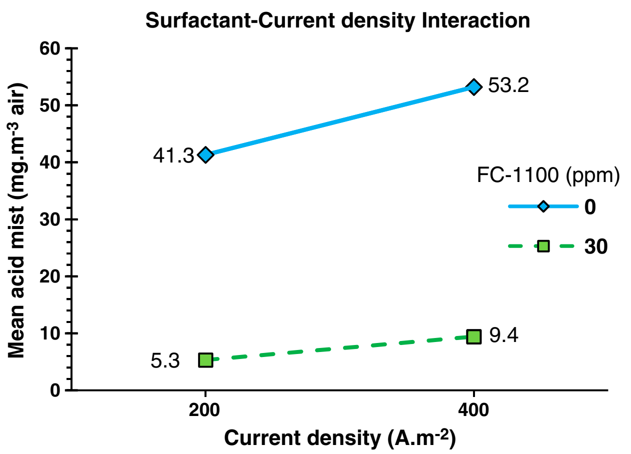

Fig. 5. The effect FC-1100 on acid mist at different current densities.

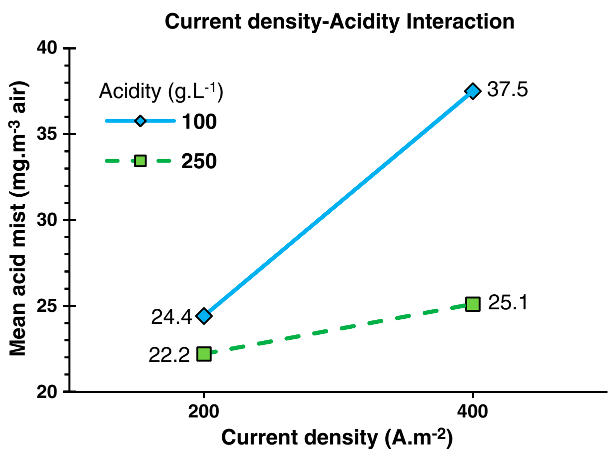

Fig. 6. The effect of solution acidity on acid mist at different current densities.

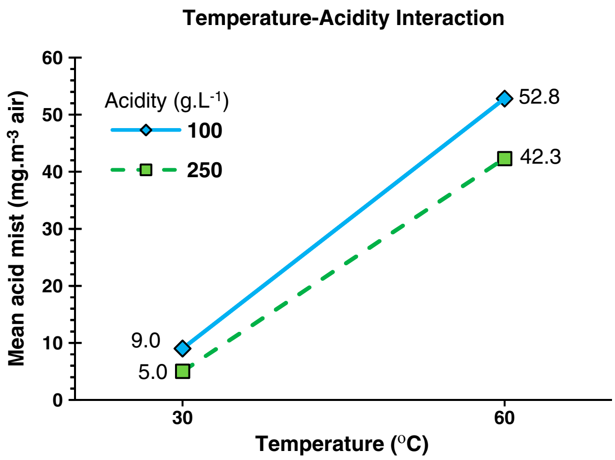

Fig. 7. The effect of solution acidity on acid mist at different temperatures.

electrolyte, the surface tension of 7 samples was measured by the Wilhelmy's plate method at two different temperatures. The averaged results are shown in Fig. 8.

It can be seen that temperature strongly influences the surface tension of the electrolyte in the absence of FC-1100. On average, the surface tension decreases by 32% when the temperature is raised from 30 to 60 °C in the absence of FC-1100. In contrast, in the presence of FC-1100 at 30 ppm, the temperature change has a negligible effect (less than 3%), as shown in Fig. 8. These observations are similar to those seen in Fig. 4 in that, in the absence of FC-1100, the difference caused in the amount of acid mist by temperature change is much larger. Both figures demonstrate a strong interaction between temperature and FC-1100.

It is important to note that, while both increasing solution temperature and addition of FC-1100 cause a significant decrease in the surface tension of the electrolyte, their effect on acid mist generation is the opposite. For example, at 30 °C the addition of 30 ppm FC-1100 reduces surface tension to 44 mN m^{-1} and results in 0.41 standard deviations reduction in acid mist generation. Increasing the temperature from 30 to 60 °C, in the absence of FC-1100, also reduces the surface tension to almost the same value (43 mN m^{-1}). However, this has resulted in an increase of 2.01 standard deviations in acid mist amount.

In the absence of a surface active agent, lower surface tension or lower surface energy, means lower amount of energy required for the generation of new surfaces. In other words, at a lower surface tension, it is more likely to generate higher number and smaller size of liquid droplets from the burst of bubbles. In addition, previous studies also show that the amount of liquid droplets produced from the burst of gas bubbles increases exponentially with decreasing diameter of the bubbles (Liow et al., 2007; Liow and Gray, 1996). That is, the burst of smaller gas bubbles produces more liquid droplets, or mist. In this study, when the temperature is increased, the surface tension is reduced. This has resulted in not only an increase in the likelihood to produce a higher number and smaller size of liquid droplets, but also a reduction in the size of the oxygen bubbles detaching from the anode, causing an increase in the amount of acid mist produced.

In contrast, the reduction in surface tension from the presence of surface active agents not only reduces the final bubble sizes but also changes the bubble burst mechanism at the free surface of the solution. When a bubble rises through the bulk solution and reaches the free surface of the solution, a thin film is produced in the top of the bubble. The stability and lifetime of this thin film is influenced by a number of factors such as surfactant concentration, surface diffusion, surface tension gradient, and drainage rate (Pugh, 1996). Generally, drainage rate decreases with the increase in bulk viscosity, surface viscosity and surface elasticity of the solution (Pugh, 1996). The latter two factors can be increased significantly by the presence of surfactant molecules at the liquid–gas interface (Pugh, 1996). Therefore, it is proposed that the presence of FC-1100 molecules in the solution reduces acid mist mainly via its effects on the thin film drainage rate through a change in the surface viscosity and surface elasticity rather than its effect on final bubble sizes. The slower film drainage and higher surface elasticity in the solutions containing FC-1100 result in the generation of a smaller number of airborne acid droplets (i.e. lesser amounts of acid mist).

3.3.2. Effect of viscosity

To investigate the counter-intuitive inverse relationship between the solution acidity and the amount of acid mist generated shown in Figs. 6 and 7, the viscosity of 12 electrolyte samples (7 low acidity and 5 high acidity solutions) was measured at three different temperatures. The averaged viscosity measurements for the two types of the electrolyte solution are shown in Fig. 9.

Fig. 9 shows as expected that the viscosity of a solution increases with the increase of its acid concentration but decreases with an increase in temperature. The results shown in Figs. 6 and 7, that is, more acid mist is generated by low acid concentration solutions regardless of the applied current density and temperature, can be

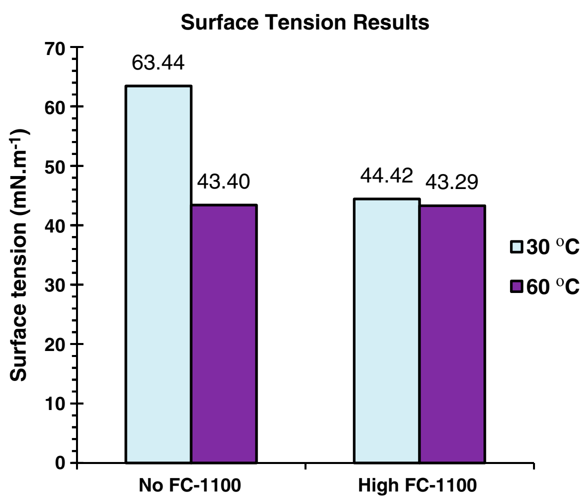

Fig. 8. The effect of temperature and FC-1100 on surface tension.

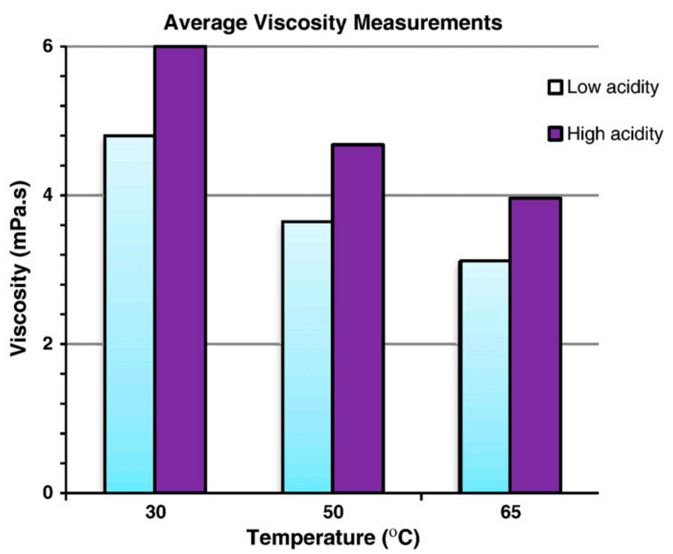

Fig. 9. The effect of solution acidity on its viscosity at different temperatures.

explained by that the amount of acid mist generated is inversely related to the viscosity of the solution.

While no quantitative relationships between the liquid viscosity and the droplet size and size distribution from the burst of bubbles can be offered at present, it is certainly true qualitatively that, the burst of more viscous liquid films or bubbles will produce less number, but in larger sizes, of droplets. This is simply because more viscous liquid films are more difficult to break-up. Further, based on Stokes' law, the terminal velocity of a rising bubble in a liquid is inversely related to the viscosity of the liquid due to the higher drag force exerted on the bubble by the surrounding liquid. As such, the average ascending oxygen bubble velocity in a more viscous liquid is lower than that in a less viscous liquid. Bubbles reaching the free surface at a lower speed would have less dynamic energy to "throw" the droplets from the bubble burst and make them airborne. The results shown in Figs. 6 and 7 imply that, at the high acidity level (high viscosity), the number of electrolyte droplets that become airborne is much less than that from the low acidity level.

It must be noted, however, that the substantial increase in acid mist with increasing temperature is not solely due to the decrease in viscosity. Based on Figs. 7 and 9 it can be seen that a 20% decrease in viscosity due to lower acid concentration in the solution results in 0.22 standard deviations increase in acid mist whereas the 34% decrease in viscosity due to temperature rise results in 1.22 standard deviations increase in acid mist. This significant increase must be attributed to the compound effect of a simultaneous decrease in both the viscosity and surface tension of the solution caused by the temperature increase.

4. Conclusions

The effect of five different operating parameters on acid mist generation was analysed using a full matrix experimental design. The temperature of the solution and the presence of FC-1100 in the solution proved to be the most influential parameters in the amount of acid mist generated. More than 90% of the variations in the acid mist generation can be explained by changes in the two parameters and their interaction.

To a lesser extent, electrical current density and solution acidity also affected the total amount of acid mist generated. Anode's age and most of the 3, 4, and 5-way parameter interactions were found to have negligible influence on the amount of acid mist.

Overall, acid mist was found to increase with temperature and current density. In contrast, addition of FC-1100 to the solutions decreased the amount of acid mist. However, it is critical to note that it is the ability of FC-1100 to increase the surface elasticity and surface viscosity, not its ability to reduce surface tension, that is responsible for the reduction of acid mist generation. The bubble burst mechanism at the free surface of the solution, which is mainly influenced by surface elasticity and surface and bulk viscosity of the solution, proved to be a critical factor in the amount of acid mist generated.

References

3M, 2007. FC 1100 acid mist suppressant. Xstrata Technology Bulletin. 3M Chile, Townsville Australia, pp. 1–19.

Al Shakarji, R., He, Y., Gregory, S., 2010. Measurement of bubble size distribution in copper electrowinning process by image analysis. In: Harre, J. (Ed.), 7th International Copper Conference. GDMB, Hamburg Germany, pp. 1237–1251.

Alfantazi, A.M., Dreisinger, D.B., 2003. Foaming behavior of surfactants for acid mist control in zinc electrolysis processes. Hydrometallurgy 69 (1–3), 57–72.

Bender, J.T., 2010. Evaluation of mist suppression agents for use in copper electrowinning. In: Harre, J. (Ed.), 7th International Copper Conference. Electrowinning and -refining. GDMB, Hamburg Germany, pp. 1271–1280.

Cheng, C.Y., et al., 2004. Evaluation of saponins as acid mist suppressants in zinc electrowinning. Hydrometallurgy 73 (1–2), 133–145.

Cohen, J., 1988. Statistical power analysis for the behavioural science. Lawrence Erlbaum Associates Inc, New Jersey.

Davenport, W.G., King, M., Schlesinger, M., Biswas, A.K., 2002. Extractive Metallurgy of Copper. Elsevier Science Ltd, London.

Davis, J.A., Eng, P., 2002. Budget quotation for a cross flow ventilation system of Sepon Copper Ltd. DESOM Systems Inc, Ontario USA.

Field, A.P., 2005. Discovering statistics using SPSS: (and sex, drugs and rock 'n' roll). ISM Introducing Statistical Methods, SAGE, London.

Harris, D.C., 2007. Quantitative Chemical Analysis. Freeman and Co, New York.

Hooper, G., 2008. In: Gregory, S. (Ed.), Quotation on 3M Matting. Blackwoods Townsville, Australia.

Hosny, A.Y., 1993. Electrowinning of zinc from electrolytes containing anti-acid mist surfactant. Hydrometallurgy 32 (2), 261–269.

Houlachi, G.E., Edeards, J.D., Robinson, T.G., 2007. Copper Electrorefining and Electrowinning, V. Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, Quebec Canada.

HSIS, 2009. Exposure Standard Documentation. Hazardous Substances Information System, Australia. Available: http://hsis.ascc.gov.au/DocumentationES.aspx?ID=578. [Accessed 5 March 2009].

Liow, J.L., Frazer, A., He, Y., Eastwood, K., Phan, C., 2007. Acid mist formation in the electrowinning of copper, Chemeca. Chemeca, Melbourne Australia.

Liow, J.L., Gray, N.B., 1996. Experimental study of splash generation in a flash smelting furnace. Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science 27 (4), 633–646.

Mella, S., Rodrigo, V., Lillo, A., 2006. Copper electrowinning in the absence of acid mist. SAME Ltd, Santiago Chile.

Montgomery, D.C., 2005. Design and Analysis of Experiments. John Wiley & Sons Inc, New York.

OSHA, 2003. Sulfuric acid exposure limits. Occupational Safety & Health Administration, Washington DC. Available: http://www.osha.gov/dts/chemicalsampling/data/CH_268700.html. [Accessed 3 March 2009].

Pugh, R.J., 1996. Foaming, foam films, anti-foaming and de-foaming. Advances in Colloid and Interface Science 64, 67–142.

Robinson, T., Lang, J., Isbell, L., 1994. Cerro Colorado Copper Company SX-EW Plant. ISA PROCESS Tankhouse, Colorado USA.

San Martin, R.M., Otero, A.F., Cruz, A., 2005a. Use of quillaja saponins (*Quillaja saponaria* Molina) to control acid mist in copper electrowinning processes: Part 2: pilot plant and industrial scale evaluation. Hydrometallurgy 77 (3–4), 171–181.

San Martin, R.M., Otero, A.F., Figueroa, M., Escobar, V., Cruz, A., 2005b. Use of quillaja saponins (*Quillaja saponaria* Molina) to control acid mist in copper electrowinning processes: Part 1. Laboratory scale evaluation. Hydrometallurgy 77 (3–4), 163–170.

Sigley, J.L., Johnson, P.C., Beaudoin, S.P., 2003. Use of nonionic surfactant to reduce sulfuric acid mist in the copper electrowinning process. Hydrometallurgy 70 (1–3), 1–8.

Sunwest, 2004. The most comprehensive solution to tankhouse emissions problems. Sunwest Supply, Arizona USA. Available: http://www.sunwesttec.com/brushes.html. [Accessed 13 April 2008].

Xie, G.X., et al., 2009. Effect of liquid properties on the growth and motion characteristics of micro-bubbles induced by electric fields in confined liquid films. Journal of Physics. D. Applied Physics 42 (11), 12.

Xu, Q., et al., 2009. Effects of surfactant and electrolyte concentrations on bubble formation and stabilization. Journal of Colloid and Interface Science 332 (1), 208–214.

The link between operational practice and maximising the life of stainless steel electrodes in electrowinning and electrorefining applications

1. J. Weston
Mount Isa Mines Limited – ISA PROCESS™ Technology
Hunter Street, Stuart, Queensland, Australia 4814
Joanne.Weston@mim.com.au

2. W. Webb
Mount Isa Mines Limited - ISA PROCESS™ Technology
Hunter Street, Stuart, Queensland, Australia 4814

ABSTRACT

The use of a permanent stainless steel cathode plate in both electrowinning and electrorefining applications has long been accepted as a proven technology for cathode copper production. Mount Isa Mines Limited is the original inventor of this technology and experience has shown these cathodes can have a life of more than fifteen years in electrorefining and ten years in electrowinning.

Correct management of the operating system and attention to detail will ensure the life of the electrode in both applications. Chloride levels in electrolyte, current density, the use of shorting frames, current distribution, harvesting patterns, and cathode-plating cycles all affect cathode plate life.

The aim of this paper is to discuss common problems encountered with electrode management, with a particular focus on electrowinning plants. Proven practical control measures, possible management solutions and operating parameters that extend the cathode operating life will be discussed. These recommendations are based on test work conducted by the ISA PROCESS™, operating experience and knowledge gained through cooperation with licensees.

INTRODUCTION

The introduction of the permanent stainless steel cathode plate in 1978 was a revolutionary development in the copper industry. This occurred in 1978 when Mount Isa Mines (MIM) undertook a complete modernisation from starter sheet to permanent cathode technology in their Townsville Copper Refinery.

The ISA PROCESS^{TM} Technology is based upon a superior cathode plate design and cathode-stripping machine. The ISA cathode plate consists of a stainless steel hanger bar that is stitch welded to a stainless steel blade. The hanger bar and part of the blade are then electroplated with copper to provide maximum electrical conductivity and corrosion resistance.

Currently ISA PROCESS^{TM} has fifty-six licensees, of which thirty-five are electrowinning plants and twenty-one are electrorefining plants. Approximately 33% of the world's copper production is produced using the ISA PROCESS^{TM}. The ISA cathode plate has applications in both electrowinning (EW) and electrorefining (ER) applications. Cathode plate longevity is directly related to operating conditions.

Operators of both electrowinning and electrorefining plants are facing similar challenges, including:

- Achieving and maintaining target copper production levels.
- Ensuring chemical and physical cathode copper quality.
- Ensuring a safe working environment for all employees.

The operational methodology to achieve these goals can at times be detrimental to the long-term service life of the cathode plate.

THE STAINLESS STEEL PERMANENT CATHODE PLATE

The latest ISA PROCESS^{TM} cathode plate design is the ISA Cathode BR^{TM} and is the lowest resistance cathode plate available in the market. The ISA Cathode BR^{TM} is based on the proven ISA design. The copper coating is thicker to provide greater corrosion resistance and the plating has been extended to the base of the lifting windows to significantly reduce electrical resistance. These improvements will provide a greater service life, but only good management practice will ensure the extended operating life of the permanent cathode plates.

LIFE EXPECTANCY OF THE ISA PROCESS™ CATHODE PLATE

The ISA PROCESS™ is based on the premise that stainless steel cathode plates are a capital item not a consumable. Cell house management in both electrowinning and electrorefining will influence the effective life of this capital investment. It has been proven that ISA PROCESS™ cathodes will perform without significant repair, for greater than ten years in electrowinning and in excess of fifteen years under electrorefining conditions.

Cathode plate life may be defined as the operating period in which the cathode plate will produce LME grade A copper at high operational efficiency. The integrity of the cathode plate assembly must be maintained. This requires attention to plate straightness, verticality, integrity of the welded joints, condition of the copper coating, stripability and overall electrical performance.

The life expectancy of the standard ISA PROCESS™ plate in electrorefining is currently beyond fifteen years in well-managed refineries. These plants do not commit to major cathode repairs except through unusual misadventure.

This is not the case in electrowinning plants because the ability to maintain a stable, ongoing production regime within the cell house is often compromised. The solvent extraction plant, heap leaching operation and in some cases the mining operations have a significant impact of the ability to operate the electrowinning plant. Subsequently the condition of the cathode plate can be compromised. The life expectancy of an ISA PROCESS™ cathode plate is up to ten years without repair compared to less than three with other cathode types.

EXTERNAL FACTORS INFLUENCING ELECTROWINNING OPERATIONS

Mining, leaching and solvent extraction processes can have overflow effects on the electrowinning operations that are not within the direct control of the EW operators. These effects can be transient, whilst others may be longer term and site specific. Failure to react promptly to such occurrences can impact on cell house operations, which may affect the integrity of the cathode plates.

Mining operations

The impact of variable mineralogy and ore grades is well recognised. Experience at Girilambone Copper Company in NSW showed that a change in crushing, stacking and heap leach irrigation methods was necessary to optimise recovery from lower grade ores with the changing ore types (Dudley, Bos & Readett, 3).

Variability of gangue minerals in heap leaching operations can be just as significant. Gangue materials may contain higher silicates, a larger percentage of fines or produce more fines in crushing (due to lower mechanical strength), higher chlorides and iron minerals (for example pyrite). These characteristics may result in:

- Reduced recovery rates and overall recovery, resulting from lower heap permeability.
- Lower heap permeability can also lead to leach solution ponding, wash outs resulting in higher suspended solids in the PLS.
- High chloride and iron levels in the PLS.

These changes can affect crud build up and impurity transfer (Cl, Mn & ferrous) to the cell house. Elevated chlorides in the cell house will increase the potential for corrosion of the cathode plate and high iron transfer will reduce the current efficiency.

Heap leaching operations

Management of the heap leaching operations is crucial in maintaining the quantity and quality of the PLS solution being delivered to the solvent extraction plant. The composition of soluble salts (other than copper) in the PLS can vary and is generally site specific. The heap leach system can be used to "filter" out many of the unwanted suspended solids in the leach solution prior to the solvent extraction plant.

Close monitoring of the heap leach system to reduce the amount of solids entering the SX plant and achieve the desired recovery rates is required. Below are general areas which require attention to achieve these targets:

- Irrigation methods - wobbler versus dripper irrigation for temperature control and recovery.
- Application rates should match heap permeability in order to reduce the occurrence of ponding and the likelihood of wash outs.
- Heap maintenance to detect quickly any problems with application rates, line failures, washouts.

Suspended solids and low copper grades in the PLS increase the difficulty of the solvent extraction operation. Suspended solids generally result in crud formation, increasing the phase break times and ultimately lead to higher entrainment levels passing through to the cell house.

Solvent extraction plant

The copper grade of the PLS can be utilised to maintain production, reduce iron transfer, organic losses, crud build up and the loads on the electrolyte filters. High copper grades in the PLS combined with low extraction rates (provided production targets are achieved) will:

- Allow lower PLS flow rates - resulting in reduced aqueous and organic entrainment due to more effective phase disengagement.
- Minimise ferric iron transfer, therefore maximising current efficiency.

- Result in longer residence times in PLS, ILS ponds which reduces suspended solids and therefore crud formation.

Crud formation can lead to increased aqueous entrainment. This can result in increased chloride levels in the electrolyte feeding the tankhouse which at elevated levels can lead to pitting corrosion of the stainless steel blade.

Increased sulphuric acid concentrations and high levels of organic entrainment in the electrolyte can be detrimental to the cathode plate, resulting in increased levels of corrosion. Higher primary flow rates can lead to larger organic losses to both the raffinate stream and to the strong electrolyte phase also increasing the likelihood of corrosion. In plants that are operated at high extraction efficiencies with low copper PLS grades, ferric iron transfer can become a significant operational problem for the electrowinning plant

SOME PROBLEMS EXPERIENCED IN ELECTROWINNING PLANTS

Repair of mechanical damage to the cathode plate is a common problem for both electrowinning and refining operator's. Problems in EW plants tend to be more severe than those of an ER plant and as a result their cathode plates generally last longer.

Problems experienced in some operations include corrosion of the stainless steel blade, corrosion of the copper coating on the hanger bar, corrosion of brazed copper to stainless joints, solution line corrosion and maintaining plate geometry.

Corrosion of copper plating and brazed copper to steel joints

Experience and plant data indicates that two of the most common problems experienced in electrowinning plants are:

- Corrosion of the brazed joints of solid copper hanger bar system
- Corrosion of the copper of the hanger bars

It is common to experience failure of the braze between the solid copper hanger bar and the plate after a relatively short time (as illustrated in Figure 1). When the hanger bar is bent and cracking of the braze occurs, crevice corrosion is accelerated through the crack. The braze material becomes anodic and corrodes, where rapid failure is possible.

The rate of corrosion of this type will be dependent upon weld quality and material choice. Corrosion of this joint results in higher resistances and poor cathode efficiency. Re-brazing of the solid copper hanger bar to the blade will repair this poor performance and prevent ultimate failure of this joint. ISA PROCESS™ cathodes are not subjected to this type of failure.

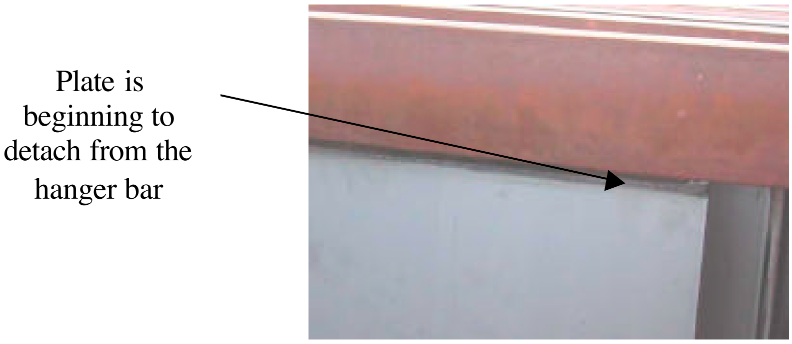

Figure 1: Corrosion of brazed joint between solid Cu bar and stainless steel plate

In some environments ISA cathodes may experience corrosion of the copper coating. This can be accelerated if the coating has been mechanically damaged in some way. The corrosion mechanism is galvanic. Often incorrect use of shorting frames can initiate this type of corrosion. This is illustrated in Figure 2 where the shorting frame has damaged the hanger bar and corrosion of the copper coating has resulted.

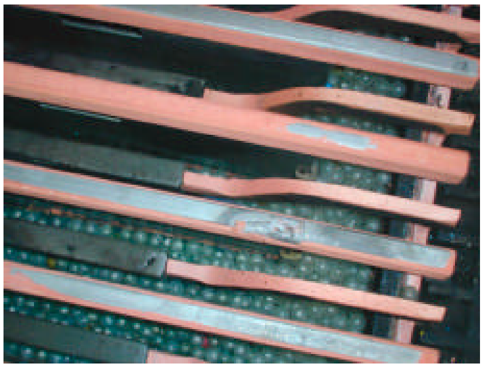

Figure 2: Corrosion of copper coating after 7 years operation

Galvanic corrosion

A review of the mechanism of galvanic corrosion, illustrates that it will occur when two dissimilar metals are connected in an electric circuit and immersed in electrolyte (Hayes, 4). The point at which the two dissimilar metals are joined is generally where the corrosion will occur first. Copper is more reactive and will act as an anode compared to the passive 316 stainless steel will take the part of the cathode (Craig and Pohlman, 2).

Corrosion of the stainless steel blades

The superior corrosion resistance of stainless steel is a result of the formation of a thin passive layer on the surface of the cathode plate. This passive layer mainly comprises of chromium oxide. If this layer is damaged and unable to rebuild itself, corrosion will occur in the unprotected areas (Hayes, 4). Great effort is then required to remove copper from corroded blades often resulting in damage to the cathode plate. Following copper removal, cathode plates are re-straightened and buffed to restore a useable surface. Figure 3 illustrates surface corrosion of the stainless steel blade.

316 stainless steel is corrosion resistant within a range of electrolyte conditions. Temperature, acid concentration and chloride levels are the key factors when considering the corrosion resistance of 316 stainless steel.

Figure 3: Surface corrosion of the cathode mother plate

Pitting and crevice corrosion

Pitting and crevice corrosion are a type of localised corrosion, where there has been a localised breakdown of the passive film. Pits are formed that are very small in comparison with the overall surface, and subsequently corrode very quickly (Aspahahani & Silence, 1). Once the localised breakdown of the protective film occurs an electrolytic cell is effectively created. The anode is the pit (small area) and the surrounding larger protected surface acts as the cathode. As the corrosion continues down the pit it is less likely that the surface in the pit is able to re-passivate.

Pitting corrosion is common in neutral and acid solutions that contain chlorides (and bromides). The chloride ions facilitate the pits by breaking down the passive film in localised areas, this is particularly so in the presence of surface imperfections. These imperfections could include such things as suspended solids, sulphides and micro crevice imperfections (Hayes, 2001).

Crevice corrosion occurs under the same conditions as pitting corrosion but only requires a small crevice for corrosion to be initiated. This is because capillary forces apply, and solution is drawn into the crevice creating an environment with stagnant solution. The supply of oxygen to the surface of the plate is restricted and the passive oxide layer is not replenished and corrosion continues to occur.

Low pH's, high chlorides, high temperatures and stagnant solutions are conducive to pitting and crevice corrosion.

Solution line corrosion

Solution line corrosion is often characterised by pits above and around the solution line (illustrated in figure 4). Pitting may be due to chlorides and organic transferred from the SX plant. It may also be due to incorrect addition of chlorides for reagent purposes, further exaggerated by the presence of organic residue in the electrolyte.

Unnecessary buffing of the entire cathode plate to overcome this 'tightness' is frequently undertaken. This practice can accelerate the surface corrosion and may result in 'prestripping' of the newly buffed plates.

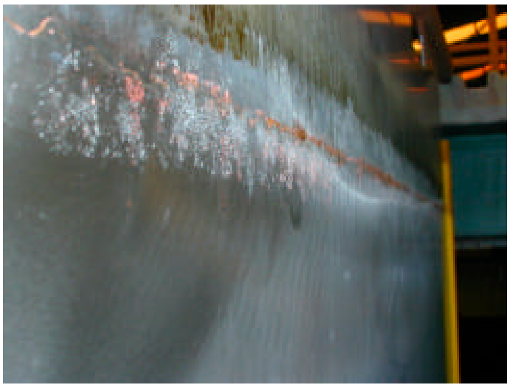

Figure 4: Solution line corrosion

Pre-stripping of the copper cathode

The ISA PROCESS™ cathodes have a surface finish that will allow for the necessary mechanical handling of the cathodes without pre-stripping. It will also enable the easy separation of the copper in the cathode-stripping machine that has been specifically designed for that purpose.

When cathode plates are buffed excessively, pre-stripping may occur. ISA PROCESS™ recommends a standard surface finish for refurbished blades, which is different to that of a brand new plate. The tendency to polish the plate to a 'mirror like' surface must be avoided. It should be noted that cathodes up to 110kg per side are routinely produced in ISA PROCESS™ plants without any pre-stripping problems.

Difficult to strip copper - "sticky copper"

At times it is difficult to strip the copper successfully from the cathode mother plate. This can be due to pitting corrosion of the blade or thin copper deposits. ISA PROCESS™ recommends an average copper cathode weight in excess of 40kg to ensure easy stripping. Without sufficient weight and thickness it may be extremely difficult to flex the copper from the plate. The copper tends to simply bend and flex with the stainless steel plate.

Sticky cathodes are often removed by manual or more aggressive mechanical means. These techniques can result in dents, bends and severe scratching of the blades. All of which will affect the plate verticality and future corrosion resistance.

INTERNAL CELLHOUSE OPERATING PARAMETERS

Within the cell house there are opportunities for operational choices that can extend the service life of the cathode plate. Where possible these practices should be employed. Those that result from limitations of the original design need to be compensated for where practical.

Harvesting sequences in electrowinning operations - current density

The operating current density at the time of copper initiation and nucleation has a significant effect on the copper quality and stripability. The chosen harvesting cycle will determine the initiation current density. There are two types of live harvesting sequences commonly employed in electrowinning:

- Harvesting the cells by lifting every third cathode
- Harvesting the cells in blocks of cathodes in thirds

<u>Harvesting by lifting every third cathode</u>

This harvesting sequence ensures that current is maintained through each anode and the subsequent current density of the cathode plates is not excessively high. Cathode currents in adjacent cells are virtually unaffected, anode currents are maintained, easy access for above cell inspection and wash down of cathodes and contacts. The results of which is a much higher cathode quality and the life of the lead anode is prolonged by a more steady and constant method of operation.

Harvesting in one third blocks

The difference lies within the current distribution of the anodes. In effect every time that one third of the cathodes are removed from the cell for stripping, that block of anodes is effectively turned off. Consequently the anodes are frequently cycled which can lead to premature spalling of the anode. This will result in reduced anode life and a greater potential for lead contamination in the cathode copper. Once lead contamination of the cathode is detected the logical step is to remove the lead from the bottom of the cells or clean individual anodes. To remove lead from the cells a shorting frame is required which leads to further anode cycling.

This method utilises a smaller crane bale and enables a shorter inlet and outlet conveyor. Loading and unloading of electrodes into the cell is simplified, resulting in a more rapid turnaround of electrodes through the cell house.

Stripping cycles

The initiation current density on bare stainless steel is extremely important when choosing stripping schedules. At high current densities in excess of the normal operating range it is possible to form nascent hydrogen. This occurs when the limiting current density for cupric ions has been exceeded. This highly reactive form of hydrogen can react with the chromium oxide film that protects the stainless steel. Once this occurs corrosion of the plate is possible, resulting in "sticky" cathodes.

If one entire cell load of cathodes is stripped one after the other in blocks, bare stainless steel is exposed to much higher current densities. It is preferable to strip one group (every third cathode) moving around the cell house, then stripping the next group the following day and so on. With this approach no bare stainless steel is exposed to the higher current densities while one group is out of the cell being stripped. In this situation if the limiting current density for cupric is exceeded and nascent hydrogen is formed, the stainless steel blade cannot be corroded because it will already have a skin of copper over it. It may be possible that the copper will be slightly corroded and perhaps result in a rougher copper deposit.

The harvesting method and stripping sequence determine the initiation current density. At lower current densities corrosion of the stainless steel blade is unlikely and the possibility of rough copper deposits is reduced.

Use of shorting frames

Shorting frames are commonly used in electrowinning operations, to take cells off line for lead scale removal and anode cleaning. The correct choice, design and proper use of the shorting frame is important in avoiding damage to the cathode plate's hanger bar.

Uniform current distribution is critical during the operation of a shorting frame. Significant damage can result from uneven current distribution resulting in elevated temperatures and melting of the bar at the point of contact. Subsequently, penetration of the copper coating will accelerate the corrosion and this is illustrated in figure 5. Extreme temperatures may also soften and weaken the braze of the solid copper hanger bar systems, making them susceptible to corrosion attack at the joint.

Certain types of shorting frames are able to compensate for variation in cathode type where the bars do not sit at the same height and should be used.

Figure 5 Damage caused to hanger bar from incorrect use of shorting frame

Frequent use of shorting frames increases the rate of anode cycling, the likelihood of lead contamination of the copper cathode and damage to the hanger bar.

Choice of acid mist control systems

There are various types of acid mist suppression systems employed by EW operators throughout the world. These include, cell covers, ventilation systems, mist suppressant reagents, bb's and balls and hoods. Associated with each of these are elements that can cause some damage to the cathode mother plate in the form of corrosion. The extent of these problems will be dependent on the specific management practices within the cell house.

Cell covers tend to limit the operation of the cell house by dictating harvesting sequencing due to the necessary removal and placement of the cell cover/hoods. The longer cathodes are out of the cell means the remaining cathodes are subjected to higher current densities for extended periods. This can result in corrosion of the stainless steel and rough copper deposits.

The use of Bb's or balls in scavenger cells requires constant cleaning to remove organic carryover. Failure to do so may result in corrosion of the stainless steel at the solution line. Organic carryover can result in an increase in acid concentration, copper depleted solution in this region that is conducive to corrosion. A thick layer of bb's/balls in the presence of high chlorides can also result in solution line corrosion.

Cathode plate maintenance

Plate straightness and verticality is of upmost importance in maintaining uniform current distribution and efficiency. A cathode plate that is not hanging vertical will result in uneven current distribution, which can lead to further problems with short-circuiting and cathode quality. Significant damage to the plates can occur if these are not straightened correctly.

Surface finish is the key factor affecting stripping performance. The initial 2B finish provides sufficient adhesion so that the cathode can be transported safely throughout the tankhouse but easily stripped by ISA PROCESS™ cathode stripping machines. Only when the copper is proving to be too difficult to strip by the normal means, should buffing of the plates to restore the surface condition be considered. As a general rule it is said that plates which do not machine strip, but are able to be hand stripped do not require surface conditioning.

The reason some plates do not machine strip is due to thin copper deposits rather than poor surface condition. In the case of thin deposits, rather than the copper flexing (shearing) off the cathode plate the copper moves with the stainless steel blade. Aging anodes, poorly maintained electrode geometry, poor current distribution and high current densities all contribute to poor physical quality cathode and may necessitate early cathode stripping.

The correct refurbishment methods are crucial. Buffing should be conducted with the appropriate buffing media, fitted to the correct machines and operated at the recommended speeds for which the media was designed. Only those areas that have a damaged surface should be buffed.

Over polishing can often result in pre-stripping of electrodes, creating a serious safety concern in the tankhouse and repercussions in current distribution. If buffing is conducted at machine speeds that are too high there is a tendency to scratch the plate. This can lead to crevice corrosion of the stainless steel blade.

Copper deposit quality

As current density and anode age increases the ability to maintain even current densities is compromised. Poor current distribution can lead rough copper deposits, increasing the probability of lead contamination and the formation of direct shorts.

Direct shorts will result in anode distortion and increase spalling of the lead anode. Subsequently, lead contamination in the cathode will increase. To overcome this problem, operators may choose to produce lighter cathodes.

Light cathodes are not as easily stripped and subsequently stripping performance may deteriorate. This deterioration may result in the perception that the plates require buffing. The amount of cathode buffing increases, which can then result in pre-stripping.

MACHINE AND DESIGN CONSIDERATIONS FOR EW PLANTS

Machine reliability, crane cycles and stripping cycle times are crucial to the successful operation of a cell house and maintaining the integrity of the stainless steel cathodes. It is important that all of the equipment operates in sequence with one another, so that one piece of element does not delay the entire process. Cell turnaround requirements and work scheduling ultimately dictates the machine capacity in the design for a new EW plant.

The crane must provide a continuous supply of cathodes to the stripping machine so that it can operate at design capacity. If the crane is unable to keep up with the stripping machines, cathodes will spend longer out of the cells than necessary. Cycle times need to compliment one another to ensure this does not occur and that cathodes have adequate time in the wash chamber. On the other hand the crane should not wait over the inlet conveyor with a rack of cathodes if the machine is not coping with the throughput. It should wait over the cell and remove the cathodes when the conveyor is able to fit another rack of cathodes. This will also ensure that cathodes are out of the cells for the shortest time possible.

Regular machine and equipment maintenance is absolutely critical for the smooth operation of the cell house and service life of the cathode plate. The design of all ISA PROCESS™ cathode stripping machines ensures that there is no damage to the ISA cathode plate and associated edge strips whilst maintaining design throughput.

CONCLUSION

Cathode plates are a capital item and should not be considered as a consumable. Careful management of the electrowinning (and electrorefining) operation will ensure the longevity of the stainless steel cathode plate and enable the production of commercially saleable cathode copper. Management practices from mining through to the electrowinning plant all play an important role in the maintenance and preservation of the permanent cathode plate.

The ISA PROCESS™ is an integrated system that combines a robust cathode plate with a safe and high performance stripping machine design. When combined with good process management the long-term effectiveness of licensed facilities is ensured.

REFERENCES

Book References

1. A.I. Asphahni and W.L. Silence "Pitting Corrosion" in Metals Handbook, Ninth Edition, Volume 13 Corrosion, ASM International, United States of America, 113-114.

2. Craig and S.L. Pohlman "Introduction" in Metals Handbook, Ninth Edition, Volume 13 Corrosion, ASM International, United States of America, 83-85.

Edited Conference Proceedings

3. K.A. Dudley, D.R. Readett and J.L. Bos, "Hyrometallurgical Processing of Copper Ores, Heap leach, solvent extraction and Electrowinning at Girilambone Copper Company", in Proceedings of the AusIMM MinPREX 2000 Conference, Melbourne, Australia.

4. Hayes, "Corrosion of Stainless Steel", Paper presented at the Seventh ISA Process User's Conference, Phoenix, Arizona, USA, 27th May - 1st June 2001.

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The sizing of oxygen bubbles in copper electrowinning

Reza Al Shakarji [a,1], Yinghe He [a,*], Simon Gregory [b,2]

[a] School of Engineering and Physical Sciences, James Cook University, QLD 4811, Townsville, Australia
[b] Xstrata Technology, Copper Refinery Limited, Hunter St, QLD 4811, Townsville, Australia

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ABSTRACT

Oxygen bubbles are formed on the anode in the copper electrowinning process. Burst of the bubbles produces acid mist in the tankhouse. While it is well acknowledged that the amount of acid mist is related to the size of the bubble, no systematic measurements have been made to quantify bubble size and its relationship with materials and process variables. This paper presents results of bubble size measurement under different operating conditions. For each of the operating conditions tested, bubbles were detected in a wide size distribution ranging from 20 μm to more than 400 μm in diameter. Statistical analyses on the measurement results showed that addition of FC-1100, a surfactant widely used in copper electrowinning to suppress acid mist, and solution temperature were the two most influential test parameters on the bubble size followed by the age of the anode. In contrast, current density and solution acidity had negligible effect.

1. Introduction

Electrowinning is an electrochemical process that is used to extract and refine metals such as Cu, Zn, Ni, Mn and Cd from their solutions. In most cases, the solution is acidic and oxidation of water molecules at the anode is the common counter reaction which results in the liberation of oxygen bubbles:

$$2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^- \quad (1)$$

The generation of oxygen bubbles generally requires a high overpotential and accounts for a considerable percentage of the energy consumption in metal electrowinning tankhouses. Moreover, the generated oxygen bubbles burst at the air/solution interface, producing highly acidic droplets of which the fine ones become airborne and form an acid mist throughout the tankhouse of the electrowinning plant.

Acid mist is highly corrosive and results in the corrosion of cathode plates, anode hanger bars, tankhouse equipment and building structures. It also poses a serious health hazard and causes extreme discomfort to the skin, eyes and respiratory systems of tankhouse workers. The effects of different process parameters on the amount of acid mist have been discussed in detail in our earlier publication (Al Shakarji et al., 2011).

Previous research results suggest that the amount of acid mist being generated is related to the size of the bursting bubbles (Liow et al., 2007). For electrowinning processes, although it is known that some operating parameters such as solution temperature can influence the size of the bubbles, there have been no systematic studies to quantify the effect of operating parameters on the size and size distribution of bubbles.

This paper reports results of bubble size measurement under different operating conditions. It also examines, quantitatively, the relationship between the median bubble size and five operating parameters in copper electrowinning. These parameters are anode age, electrical current density, solution temperature, sulphuric acid concentration of the solution, and the presence of a typical chemical mist suppressant such as FC-1100.

2. Experimental

2.1. Equipment setup

The copper electrowinning process was replicated in a bench-scale tank (EW cell). The equipment used in this investigation and its arrangements are shown in Fig. 1.

A peristaltic pump and four submersible heaters were used to maintain consistency in the composition and temperature of the solution for the duration of each test. To replicate industrial operations Pb–Ca–Sn alloy and 316 L stainless steel were used as anode and cathode, respectively (Houlachi et al., 2007). Areas of 100 mm wide and 150 mm long of the sides of electrodes facing each other were exposed to the solution and the rest of the immersed electrodes were isolated from the solution. This arrangement allowed

* Corresponding author. Tel.: +61 7 47814270; fax: +61 7 47816788.
E-mail addresses: reza.alshakarji@my.jcu.edu.au (R. Al Shakarji), yinghe.he@jcu.edu.au (Y. He), sgregory@xstratatech.com (S. Gregory).
[1] Tel.: +61 422347562; fax: +61 7 47816788.
[2] Tel.: +61 7 47589530; fax: +61 7 47589501.

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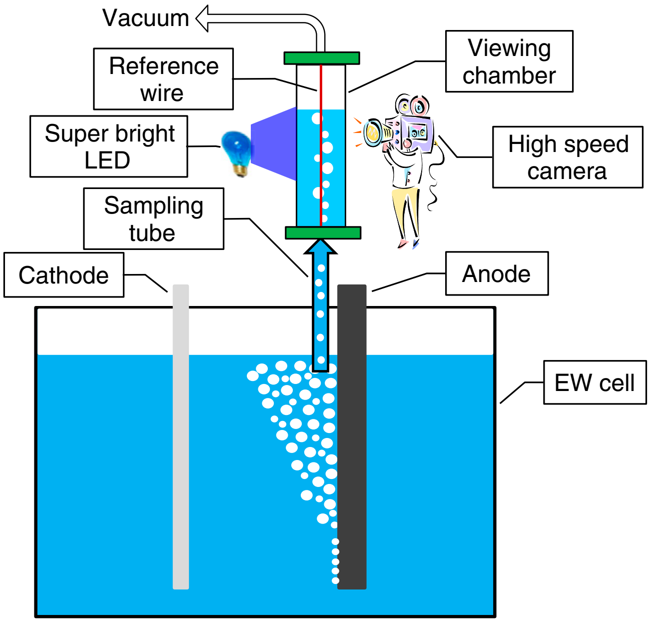

Fig. 1. A schematic view of equipment setup (not to scale).

a precise and controlled electrical current flow through the solution via the specified electrodes surfaces.

For each set of experiments a fresh batch of solution was synthesized containing 45 g L^{-1} Cu, 15 mg L^{-1} Guar gum, 20 ppm Cl, 100 ppm Co, and various amounts of sulphuric acid. The concentration of Cu, Guar gum, Cl and Co in the synthesized solution was similar to the electrolyte solutions found in most copper electrowinning tankhouses worldwide (Robinson et al., 1994). The sulphuric acid concentration in the solution, however, was one of the five selected variables and its concentration differed from that of a typical copper electrolyte solution.

To measure bubble sizes via image analysis, the generated oxygen bubbles were transferred from the EW cell to a viewing chamber. A high-speed camera (RedLake MotionXtra HG-100K) with a special macro lens and super bright blue LEDs were utilized to capture images of the rising bubbles in the viewing chamber.

2.2. Experimental design

The main goal of the present work was to compare, quantitatively, the effect of different operating parameters on bubbles sizes during a typical copper electrowinning process. To fully explore the main effect of each individual parameter as well as any possible interaction effects, the 2 K factorial method was used to determine the number of required experimental conditions (Montgomery, 2005). Based on this method, the test parameters were examined at two levels (low and high). Table 1 lists the five selected parameters and their low and high level values.

The values shown in Table 1 were selected so that the midpoint between low and high levels of each parameter represented the typical value used in most copper electrowinning tankhouses (Houlachi et al., 2007). For example, a sulphuric acid concentration in the electrolyte solution of about 170 g L^{-1} is typically used in most copper electrowinning operations. Thus, the low and high limits of solution acidity for the experiments were set at 100 and 250 g L^{-1}, respectively.

Based on the 2 K factorial method, 32 parameter combinations were required to fully examine the effect of five parameters at two levels. For reliable data analysis, a minimum of two replicates were required for each test condition. Hence, 64 tests were conducted to determine the significance of each parameter and also to identify any significant interactions among the selected parameters.

For each of the 64 experiments, at least two sets of high resolution photos were taken by the high-speed camera. The images were taken at 10 min intervals at a rate of 250 frames per second while the experiment was being conducted. To ensure that the same bubbles were not accounted for more than once, only one photo was selected per 100 consecutive frames (i.e. 3 to 5 photos were selected from each set of images of each experiment) for image analysis.

Table 1
The selected test variables and their values.

No	Examined parameter	Low	High
1	Anode age (months)	0	6
2	Current density (A m^{-2})	200	400
3	Temperature (°C)	30	60
4	Acidity (g L^{-1})	100	250
5	FC-1100 (ppm)	0	30

2.3. Bubble sizing process

A flexible silicon tube (sampling tube in Fig. 1) was used to transfer the bubble-containing solution from the EW cell to the viewing chamber. One end of the sampling tube was placed about 10 mm underneath the free surface of solution near the surface of the anode while the other end was connected to the bottom of the viewing chamber. By applying a gentle vacuum to the viewing chamber, the bubble containing solution was drawn from the EW cell to the viewing chamber at low flow rates. The large internal diameter of the sampling tube (5 mm) and the low solution flow rate, from the EW cell to the viewing chamber, ensured no bubble breakage or coalescence occurred during the bubble transfer process. Thus, bubbles observed in the viewing chamber were true representatives of those generated in the EW cell.

The high speed camera was then used to capture 800 × 600 pixel images. Each image taken from the rising bubbles in the viewing chamber contained about 100 bubbles on average (more than 300 bubbles in some cases). A MATLAB based program was developed to automate the analyses of the captured images. The developed program was able to process the images in grey scale format directly from the camera. The software was designed to take into account the uneven background illumination and to distinguish the boundaries of each bubble from its surroundings.

A thin copper wire, 130 µm in diameter, was fixed inside the viewing chamber adjacent to the solution's entrance. The diameter of this wire was used as a reference to determine the size of the bubbles captured in each image. The developed software was able to process each image in a few seconds and export the raw data of bubble diameters (in µm) to an Excel file. The software also indicated the detected bubbles with blue lines along the boundaries of each bubble and displayed the bubble diameter (in µm) next to it (Fig. 2). These processed images were used to visually inspect the results of the bubble sizing process.

To ensure the accuracy of the developed bubble sizing program, ImageJ (an open source image analysis software) was used to manually determine the bubble sizes of three randomly selected images. The results of the automated and manual bubble sizing were statistically identical.

3. Results and discussion

3.1. Overall statistical analysis

In total, more than 54,000 bubbles were sampled and their sizes measured. The diameter of the bubbles ranged predominantly from 26 µm up to 182 µm, on average, for each of the 64 experiments.

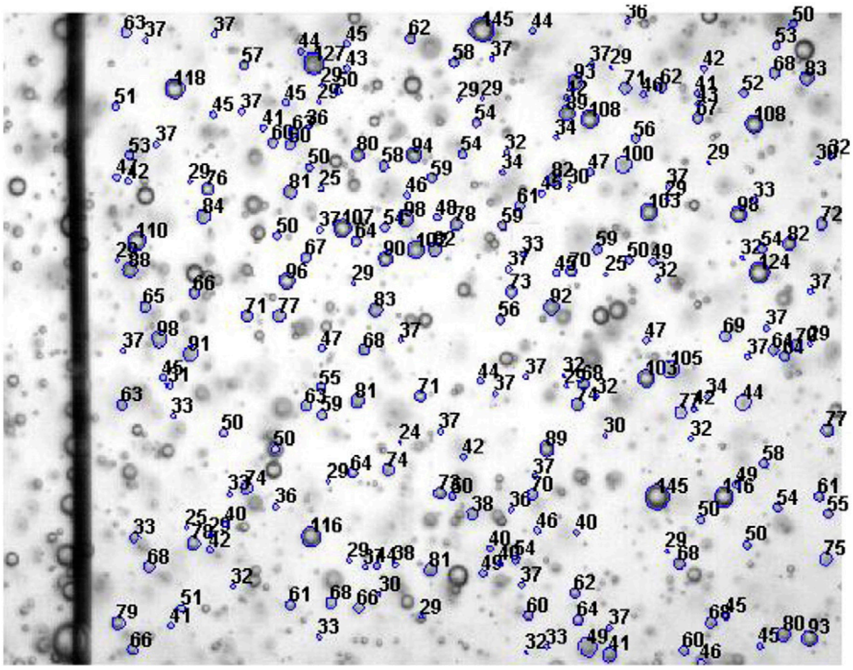

Fig. 2. A processed image with 250 detected bubbles and the reference wire (the vertical black line) appearing on the far left.

However, there were cases where the smallest detected bubble was 20 µm and the largest one was 404 µm. On average, 50% of the detected bubbles had a diameter of 53 µm or less (i.e. the grand median value). A typical bubble size distribution and cumulative percentage graph is shown in Fig. 3.

There was a relatively strong positive skewness (1.7 on average) in all the collected data samples, similar to that shown in Fig. 3. Therefore, median values were selected instead of mean values to represent the average bubble size for each experiment. The small difference between the medians of replicates of a test condition, which ranged from 0.00 µm up to 5.24 µm with the average being 2.17 µm, was a good indication of the high repeatability of the conducted experiments.

Fig. 4 illustrates the median bubble diameter (the bold black line inside each box), the lower and upper quartiles (the lower and upper edges of each box), the lower and upper extremes (the lower and upper whiskers), and also the outliers (the stars) for each of the 32 experimental conditions. The values of median bubble diameters ranged from 43 µm to 66 µm. Regardless of the applied operating conditions, 95% of the generated bubbles were less than 106 µm in diameter. It must be noted that the outliers were neither the result of error in the bubble sampling process nor the image analysis procedure. Live video footage taken from the surface of an immersed operating anode proved the existence of such unusually large bubbles. More details about these outliers can be found in our previous publication (Al Shakarji et al., 2010).

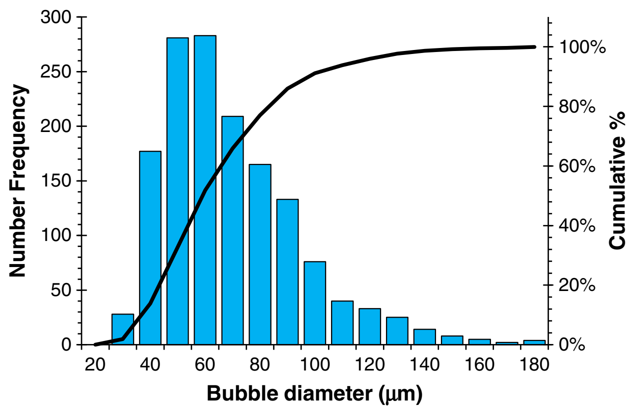

Fig. 3. Bubble size distribution and cumulative percentage graph for experiment No 9 (parameter values: new anode, 200 A m^{-2} current density, 60 °C solution, no FC-1100 and 100 g L^{-1} sulphuric acid concentration).

A 5-way ANOVA analysis was performed on the raw experimental data to determine the full effect of test parameters on the average bubble size. To quantify the magnitude of the effect of each of the 32 parameter combinations, Pearson's r value was calculated for each case based on its ANOVA's mean square value (Field, 2005). Cohen classifies the magnitude of a parameter's effect into three categories of small, medium and large (Cohen, 1988). These categories correspond to Pearson's r values of 0.1, 0.3 and 0.5 respectively (Cohen, 1988). Parameter combinations with Pearson's r value greater than 0.10 are shown in Fig. 5.

FC-1100 and solution temperature, having the highest r values in Fig. 5, were the most influential parameters in determining the final bubble sizes. To a lesser extent, anode age also influenced the final bubble sizes. Current density and solution acidity, with Pearson's r values of 0.04 and 0.05 respectively (not shown in Fig. 5), had negligible effect on the detachment size of bubbles.

The full factorial ANOVA analysis not only examined the effect of individual parameters but also all the possible parameter interactions. This analysis returned an R^2 value of 0.951, which meant the variations made in the test parameters of the conducted experiments could explain more than 95% of the bubble size variations measured in the test series.

3.2. Effect of individual parameters on bubble size

To assess the effect of individual test parameters on the bubble size, the average median bubble diameter for each level of a parameter was calculated. Each bar in Fig. 6 represents the averaged median bubble diameter from 32 independent experiments.

3.2.1. FC-1100

FC-1100 was the only parameter that had a large effect, based on Cohen's classification, on the average bubble sizes. The presence of FC-

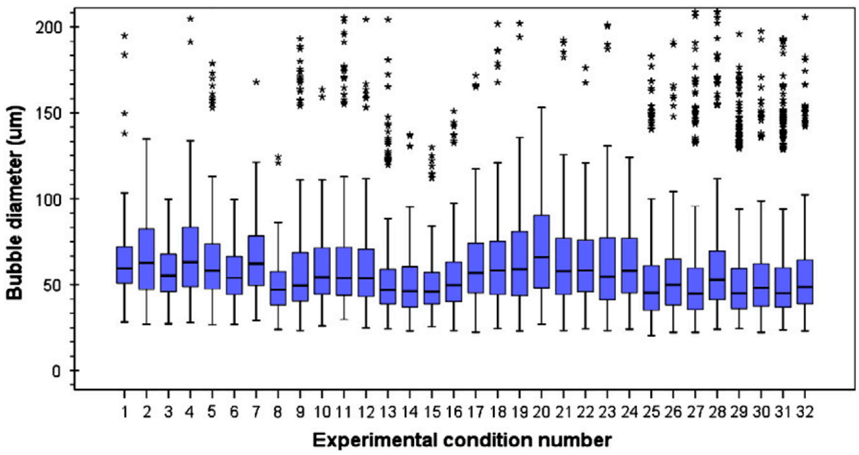

Fig. 4. Bubble size distribution under 32 different operating conditions.

1100 in the solution reduced the average bubble diameter by 9.3 μm. This result was largely attributed to the ability of FC-1100 to reduce the surface tension of the electrolyte from 63 mN m^{-1} to 44 mN m^{-1}. The near parallel solid lines in Fig. 7 implied that, within the tested range, the effectiveness of FC-1100 in reducing the final bubble sizes was independent of the solution temperature.

The bubble size distribution, in addition to the average bubble size, was also considerably reduced in the presence of FC-1100 (Fig. 8). It was proposed that the presence of FC-1100 molecules reduced the surface tension of the solution to a degree that resulted in less variation in the three phase contact angle on the anode, leading to the generation of more uniformly sized bubbles (i.e. smaller standard deviation).

3.2.2. Temperature

Solution temperature with a Pearson's r value of 0.30 was the second most influential parameter in determining the final size of a bubble (Fig. 5). Changing the solution temperature caused a relatively large difference in the average bubble diameter. Raising the temperature of the solution from 30 °C to 60 °C resulted in 3.7 μm reduction in the average bubble sizes, equivalent to 0.150 standard deviations (Fig. 6).

Similar to the presence of FC-1100, when temperature of the solution was raised from 30 °C to 60 °C, surface tension of the electrolyte solution decreased from 63 mN m^{-1} to 44 mN m^{-1}. Therefore, it was postulated that the decrease in the average bubble size at higher temperature was mainly due to the decrease in the surface tension of the solution. The large reduction in surface tension

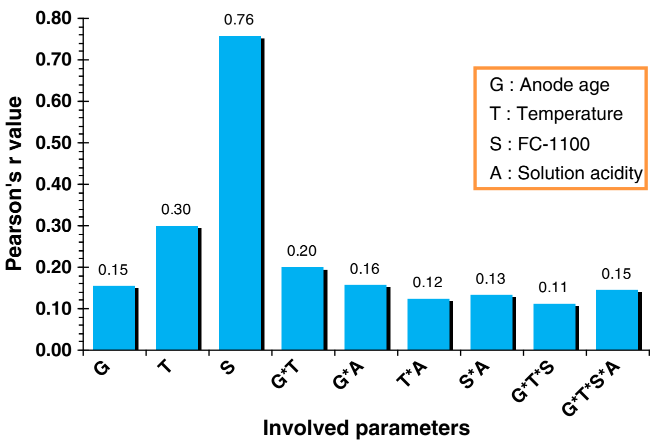

Fig. 5. Quantitative comparison of the most influential parameters and parameter interactions on the average bubble size.

due to temperature rise was also expected to result in less variation in the three phase contact angle, leading to the generation of more uniformly sized bubbles. This expectation was confirmed by data presented in Fig. 9 where bubble size distribution was noticeably less (smaller box and whiskers) in high temperature electrolyte solution.

3.2.3. Anode age

The experimental results shown in Fig. 6 suggested that bubbles generated on an old anode were, on average, 2.0 μm (0.089 standard deviations) larger than those generated on a new anode. The ANOVA analysis resulted in a Pearson's r value of 0.15 for the anode age which meant this parameter had a small/medium effect on the final size of a bubble. It was postulated that anode age affected the detachment size of a bubble by influencing the liquid–solid–gas contact angle which in turn influenced the balance of the forces acted on the bubble. SEM images revealed that the surface of an old anode was highly uneven and covered with voids and micro cracks whereas the surface of a new anode was relatively smooth and even (Fig. 10).

It was likely that the small cavities and cracks on the surface of the old anode provided much higher number of nucleation sites for the bubbles, leading to "forced" coalescence of the bubbles during their growth on the anode immediately prior to their detachment due to insufficient distances between neighbouring bubbles on the anode. Similar observations were reported by Huet where mean detachment radius of electrolytic bubbles increased with the surface roughness of nickel electrodes (Huet et al., 2004).

It is important to note that, regardless of the age of the anodes or operating conditions, bubble size distribution was relatively large, ranging from 20 μm to more than 400 μm (Fig. 4). The heterogeneities in both the chemical composition and the surface roughness of the anodes were believed to be the main reasons for such wide bubble size distributions. The anodes were Pb–Ca–Sn cold rolled alloys, either the surface roughness or the distribution of the three elements was very unlikely to be even on the surface of the anodes after the rolling process.

3.2.4. Solution acidity and current density

It is worth noting that, within the ranges tested in this study, both the solution acidity and the current density had negligible influence on the bubble size. Solution acidity could affect the bubble size only through the change it could cause in the solution viscosity. Kazakis et al. reported a noticeable difference in the average bubble size only when the viscosities of the test solutions were considerably different, e.g. the difference between their viscosities was more than 600% (Kazakis et al., 2008). Rheological tests of the copper electrolyte solutions, however, showed that high acidity solutions were only 21% more viscous than low acidity solutions. Therefore, it was suggested

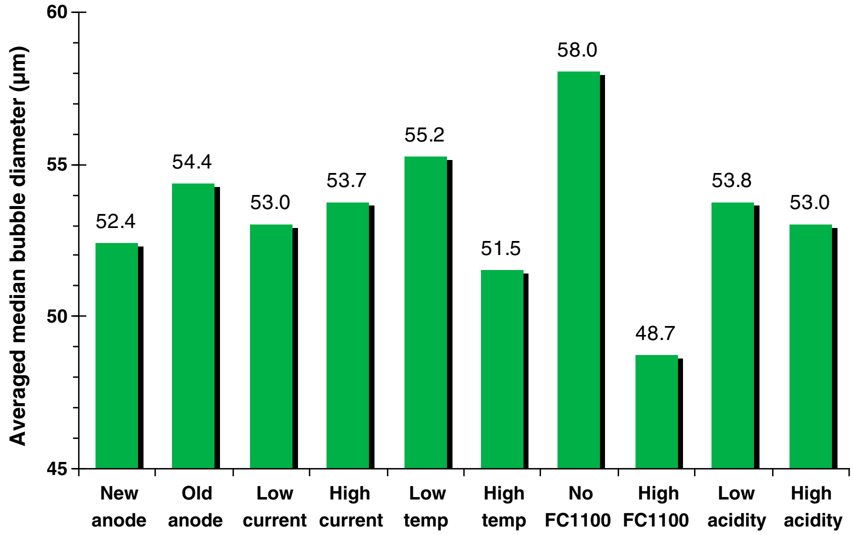

Fig. 6. Average bubble diameter at different operating conditions.

that a much larger difference in the solution acidity, and hence the viscosity, was required to observe a noticeable difference in the average size of the bubbles generated during the copper electrowinning process.

Based on Faraday's law, increasing the electrical current density would increase the amount of oxygen produced at the anode (Harris, 2007). Consistent with our results presented previously, within the range of 200 and 400 $A m^{-2}$, a change in the current density had caused only a change in the bubble nucleation rate and hence the number of bubbles generated per unit time. The final size of the bubbles changed little with current density (Al Shakarji et al., 2010).

3.3. Effect of parameters' interaction on bubble size

Few publications in this field studied the interactions that exist among the test parameters. The full factorial ANOVA analysis showed that more than 22% of variations in bubble sizes recorded in the test series were due to the interactions between the test parameters.

With a Pearson's r value of 0.20, the anode age–temperature interaction (G*T) was identified as the most significant parameter interaction. The results are shown in Fig. 11.

It can be seen that, on an old anode, increasing the temperature of the solution from 30 °C to 60 °C resulted in a relatively large decrease (more than 0.247 standard deviations) in the average bubble diameter. In contrast, the same increase in the solution temperature resulted in a much smaller decrease (about 0.049 standard deviations) in the average bubble diameter on a new anode.

The G*T interaction not only affected the average size but also the size distribution of bubbles. Size distribution of bubbles formed on the old anode was much wider at low solution temperature in comparison to that of high solution temperature (i.e. larger box and whiskers at low solution temperature). In contrast, the temperature of the solution had a relatively small effect on the size distribution of bubbles formed on a new anode (i.e. similar box and whiskers sizes at low and high temperatures).

The decrease in the average bubble size and its distribution with temperature rise was due to surface tension reduction as explained earlier. Consistent with observations made by other researchers (Drelich and Miller, 1994; Meiron et al., 2004), the strong interaction between anode age and solution temperature was believed to be mainly due to the effect of anode's surface morphology on the three phase contact angle.

The effect of the anode's surface morphology (i.e. anode age) on bubble size and its distribution was much more evident at low solution temperature (Fig. 11) since the overall surface tension was higher at lower temperature.

One of the other important interactions was the T*A interaction. The decrease in the average bubble size and its distribution due to temperature rise was not the same for the low and high acidity solutions (Fig. 12). The average size and size distribution of bubbles were more strongly affected by temperature rise in low acidity solutions than in high acidity solutions.

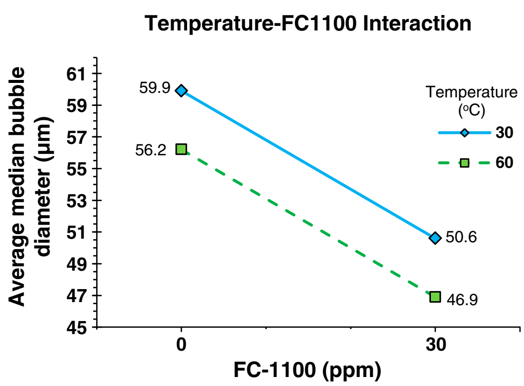

Fig. 7. The effect of FC-1100 on bubble size at different temperatures.

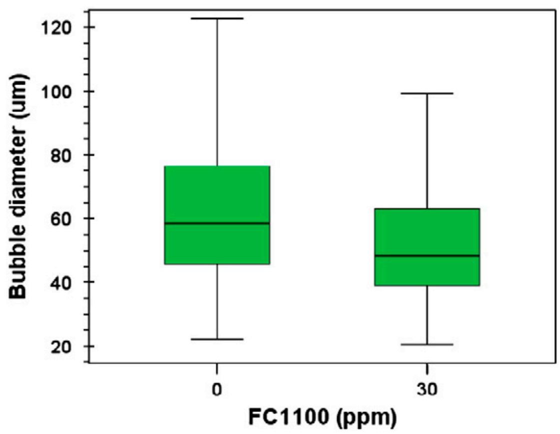

Fig. 8. Effect of FC-1100 on bubble size distribution (not including outliers).

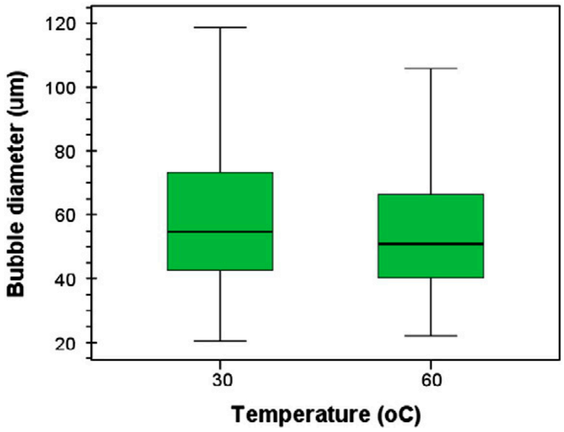

Fig. 9. Effect of solution temperature on bubble size distribution (not including outliers).

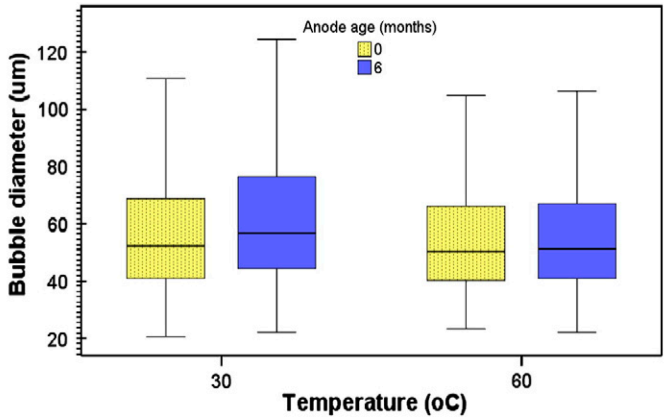

Fig. 11. The interaction between anode age and temperature.

Surface tension and viscosity were both known to influence the final size of a bubble (Xie et al., 2009; Xu et al., 2009). Temperature affected both surface tension and viscosity whereas acidity only affected viscosity. Therefore, the T*A interaction was expected to be the result of surface tension and viscosity interaction. The surface tensions of low and high acidity solutions were measured at two different temperatures (Fig. 13).

It is general knowledge that surface tension of a liquid is a function of not only its composition but also its temperature. Measurements showed that surface tension of a low acidity solution was higher than that of a high acidity solution at 30 °C (Fig. 13). However, surface tensions of the two solutions were almost the same at 60 °C. In other words, temperature had a more profound effect on the surface tension of low acidity solutions than that of high acidity solutions. These observations were similar to those seen in Fig. 12 in that, in low acidity solutions, the differences in the average bubble size and bubble size distribution caused by temperature rise were much larger. Both figures demonstrated a strong interaction between temperature and solution acidity.

The surfactant–solution acidity (S*A) interaction had a Pearson's r value of 0.13. The interaction between FC-1100 and solution acidity is illustrated in Fig. 14.

In the absence of FC-1100, although bubble size distribution was slightly larger in high acidity solutions, the average bubble sizes generated in the low and high acidity solutions were very similar. In the presence of FC-1100, bubbles generated in high acidity solutions were on average 0.101 standard deviations smaller in diameter than those generated in low acidity solutions. Xu et al. also reported similar observations when studying the effect of NaCl concentrations on bubbles generated from a sparger in the presence of fixed amounts of sodium dodecyl sulphate surfactant (Xu et al., 2009). The higher ionic concentration at high acidity solutions was speculated to result in closer packing of the surfactant molecules by reducing the repulsive forces between them (Xu et al., 2009). In our case, bulk concentration of FC-1100 in high acidity solutions might be lower, resulting in more FC-1100 molecules packing at the interface. This can be inferred from the fact that the average surface tension of low acidity solutions is higher than that of high acidity solutions. The closer packing of the surfactant molecules at the oxygen/solution interface lowers the surface tension and results in smaller bubbles.

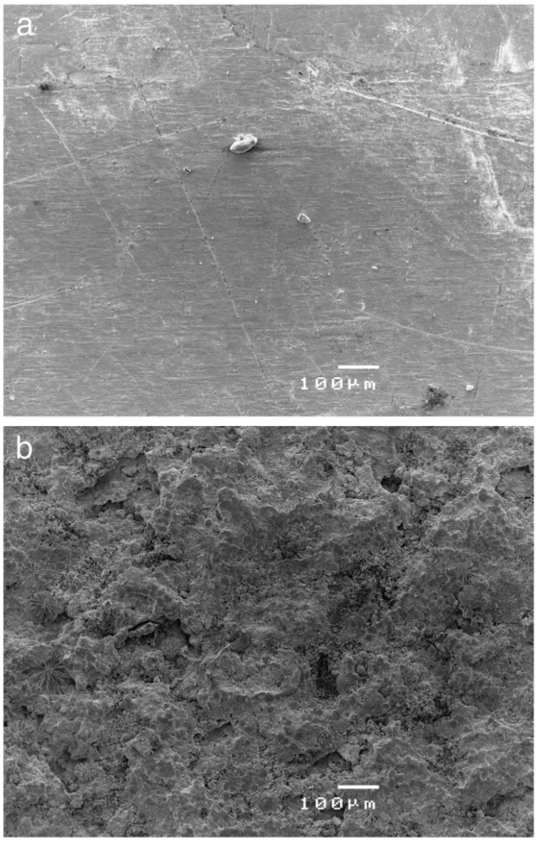

Fig. 10. The surface morphology of (a) a new anode (b) an old anode.

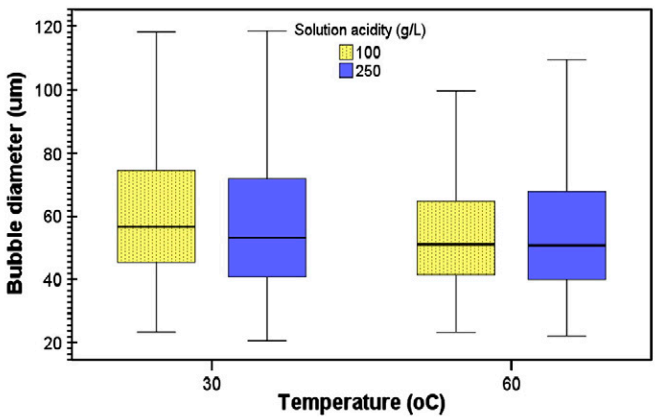

Fig. 12. The interaction between temperature and solution acidity.

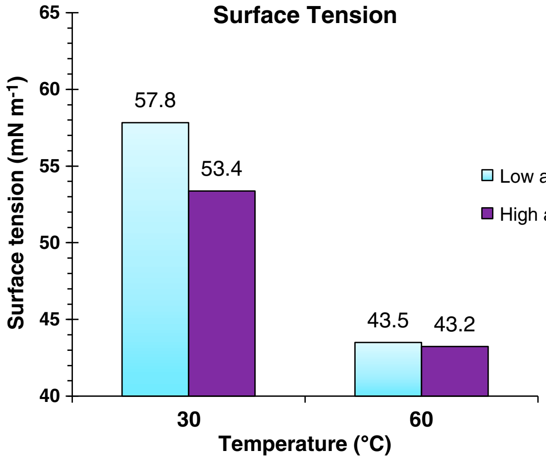

Fig. 13. Effect of temperature and acidity on surface tension.

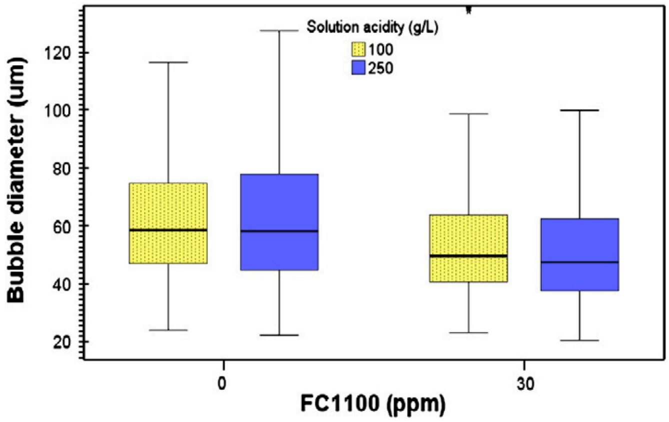

Fig. 14. The interaction between FC-1100 and solution acidity.

4. Conclusions

A high-speed camera and image analysis software were used to measure the size of the bubbles generated during the copper electrowinning process. Measurements, made under a variety of operating conditions, showed that of the five test parameters, FC-1100 and solution temperature had the most significant effect on the average size of the oxygen bubbles. Bubble size and bubble size distribution were noticeably reduced in the presence of FC-1100 or when the solution temperature was increased. FC-1100 and solution temperature both influenced bubble sizes by reducing the overall surface tension of the solution. To a lesser extent, anode age also influenced the detachment size of bubbles. Older anode generated larger bubbles and wider bubble size distributions mainly due to its surface roughness variations.

The data produced by the present work can be used to investigate the correlation between bubble size and the amount of acid mist, facilitating the design of strategies for minimizing acid mist generation in the tankhouse. The data can also be used to calculate the rate of bubble generation and release under a variety of operating conditions. Such information would be extremely useful in simulating the flow pattern of electrolyte solution between electrodes, which can be utilized to enhance the design of the electrodes and cells leading to improved electrolyte flow and copper quality at higher current densities.

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References

Al Shakarji, R., He, Y., Gregory, S., 2010. Measurement of bubble size distribution in copper electrowinning process by image analysis. In: Harre, J. (Ed.), 7th International Copper Conference. GDMB, Hamburg Germany, pp. 1237–1251.
Al Shakarji, R., He, Y., Gregory, S., 2011. Statistical analysis of the effect of operating parameters on acid mist generation in copper electrowinning. Hydrometallurgy 106 (1–2), 113–118.
Cohen, J., 1988. Statistical Power Analysis for the Behavioural Science. Lawrence Erlbaum Associates Inc, New Jersey.
Drelich, J., Miller, J.D., 1994. The effect of solid surface heterogeneity and roughness on the contact angle/drop (bubble) size relationship. Journal of Colloid and Interface Science 164 (1), 252–259.
Field, A., 2005. Discovering Statistics Using SPSS. SAGE Publications Ltd., London.
Harris, D.C., 2007. Quantitative Chemical Analysis. Freeman and Co., New York.
Houlachi, G.E., Edeards, J.D., Robinson, T.G., 2007. Copper Electrorefining and Electrowinning, V. Canadian Institute of Mining, Metallurgy and Petroleum, Quebec Canada.
Huet, F., Musiani, M., Nogueira, R.P., 2004. Oxygen evolution on electrodes of different roughness: an electrochemical noise study. Journal of Solid State Electrochemistry 8 (10), 786–793.
Kazakis, N.A., Mouza, A.A., Paras, S.V., 2008. Experimental study of bubble formation at metal porous spargers: effect of liquid properties and sparger characteristics on the initial bubble size distribution. Chemical Engineering Journal 137 (2), 265–281.
Liow, J.L., Frazer, A., He, Y., Eastwood, K., Phan, C., 2007. Acid Mist Formation in the Electrowinning of Copper. Chemeca, Chemeca, Melbourne Australia.
Meiron, T.S., Marmur, A., Saguy, I.S., 2004. Contact angle measurement on rough surfaces. Journal of Colloid and Interface Science 274 (2), 637–644.
Montgomery, D.C., 2005. Design and Analysis of Experiments. John Wiley & Sons Inc, New York.
Robinson, T., Lang, J., Isbell, L., 1994. Cerro Colorado Copper Company SX-EW Plant. ISA PROCESS Tankhouse, Colorado USA.
Xie, G.X., Luo, J.B., Liu, S.H., Guo, D., Li, G., Zhang, C.H., 2009. Effect of liquid properties on the growth and motion characteristics of micro-bubbles induced by electric fields in confined liquid films. Journal of Physics D — Applied Physics 42 (11), 12.
Xu, Q., Nakajima, M., Ichikawa, S., Nakamura, N., Roy, P., Okadome, H., Shiina, T., 2009. Effects of surfactant and electrolyte concentrations on bubble formation and stabilization. Journal of Colloid and Interface Science 332 (1), 208–214.

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CONTACT

Glencore Technology Pty Limited
ABN 65 118 727 870

Level 10, 160 Ann St
Brisbane QLD 4000
Australia

T. +61 7 3833 8500
F. +61 7 3833 8555
E.isakidd@glencore.com.au

Chile · T. +56 2 2342 9000
Toronto · T. +1 416 775 1666
South Africa · T. +27 11 772 0555
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