Advances in Design of Copper–Cobalt Hydrometallurgical Circuits: Copper Circuits

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Copper–cobalt hydrometallurgy has seen a resurgence in recent years with the development of projects in Zambia and Democratic Republic of Congo. Many of the flowsheets are unique in their use of hydrometallurgical techniques to improve performance compared with older methods that were in use. The emphasis has moved from direct copper electrowinning, with multiple sequential stages to achieve 'low' copper losses in the circuit bleed and leached tails discharge. Other significant developments have been in methods of control of the agitation-leach water balance. The ability to manufacture acid-resistant mills has allowed recycle of solvent-extraction raffinate directly into the mill, with elimination of pre-leach thickener and 'new' water contained in the underflow. Other internal recycles of acidic solutions have been developed to further improve water management. A new water management tool is the use of acidic tails disposal. Not only does this this reduce the new water input, but leaves a legacy of a reusable resource and substantially reduces the overall project carbon footprint. All stages of the process, from comminution to final copper recovery, have seen improvements in technologies, equipment and the economics of copper production.

INTRODUCTION

The new generation of copper–cobalt hydrometallurgy plants in Zambia and the Democratic Republic of Congo (DRC) have made more changes to the processes and equipment design than at any other stage in the past. New process steps have been implemented at many projects, while equipment selection and detailed design changes have been wide ranging, depending on the client and the engineer. Some have been very successful while others have had to be optimised during operation. The most recent plants have built upon the successes of the pioneer operations to generate model agitation-leach processes with high recoveries, low reagent consumption, a controlled water balance and a lower carbon footprint. This paper discusses the major advances in the copper circuits.

COMMINUTION EQUIPMENT

Materials Handling

The comminution circuits of many of the first-generation new plants were based on the experience from African underground metalliferous and open-cut coal mines where there is little clay in the mined material. The chutes and hoppers were designed with 'standard' criteria and detailing. The near-surface oxide ores have been subjected to long-term meteoric weathering, with clay minerals a significant proportion of the alteration processes. As a result, there were a number of serious issues with chute and hopper blockage and overall low utilisation and productivity of the materials handling systems.

The technology for testing of ores to provide design criteria is well established (Miller, 1994). It not only provides the minimum chute and hopper *valley angles,* but also the key criteria for mass flow in bins, hoppers and stockpiles. The latter needs the stockpile reclamation equipment to provide a diagonal measurement that is greater than the critical pipe dimension. For surface-weathered ores, with significant clay content (greater than 5%), the critical pipe can be above 20 m diameter. If the diagonal is less than the critical pipe dimension, a vertical pipe will form (a 'rat' hole'), limiting the live capacity of the stockpile. Other structural information on dynamic pressures during discharge from storages allows appropriate selection of forces on structures and equipment.

Use of the testing results has developed a set of first round criteria that provides for appropriate layout allowances in studies and initial designs:

- minimum chute and hopper valley angles of 65°;
- critical stockpile pipe dimensions of more than 20 m;
- reclaim chutes with a minimum relief of 1:50 in the direction of flow;
- need for apron feeders under bins and stockpiles to cope with the mass-flow pull-out torque and pressure.

Primary Crushing and Treatment

To handle and crush the sticky clayey run-of-mine (ROM) ores, a number of techniques have been tried to minimise the materials handling issues between the mine truck and the milling equipment. The issue can be extremely severe, with wet compacted ore difficult to discharge from the trucks (Miller, 2001). In this case, both scraping (with a modified excavator arm) and hydraulic assistance were needed to move the ore into the dump hopper and out to the primary crusher. Other ROM wet screening operations were retrofitted to three operating plants near Lubumbashi. The −5 mm was pumped directly to the mill or scrubber discharge as part of the ROM make up.

The primary crusher has traditionally been a jaw crusher, but the sticky nature of the ores has meant that this type of equipment can block ("pagging") with consolidated clay and fines. To overcome this problem, large slow rolls crushers have been used. These are more tolerant of sticky material build up; however, they have accelerated wear when hard or siliceous larger particles are crushed. Operating times as short as two weeks before replacement of rolls have been reported (Miller, 2001). A specific crusher for harder but sticky ore has been developed by one suppliers. The 'hybrid' crusher is a rolls crusher, but with an adjustable gap, similar to a jaw crusher (Sandvik, 2018).

After the primary crusher, some of the earlier agitation-leach and dense medium separation (DMS) plants used a scrubber before the next stage of comminution. For DMS plants, secondary and tertiary crushing is conducted 'dry' after the scrubber, with the crushed product wet re-screened with the scrubber discharge. The circuit is stable with intermediate storage before the DMS plant; however, if the next stage of comminution is a milling operation, the fines from the scrubber are fed directly to the mill discharge sump. This feed can be intermittent, in both solids and flow, due to the lower utilisation of the scrubbing/screening plant than the mill itself. As a result, it is very difficult to optimise the mill set up. One operation has bypassed the initial scrubbing and secondary/tertiary crushing plant, and converted the ball mill to a primary crushed ore semi-autogenous (SAG) mill. Another operation uses continuous surface miners to extract the ore (Mining Data Online, 2018). The surface miners also act as primary crushers, delivering material suitable for direct feed to a SAG mill, without further primary comminution.

LEACHING AND COUNTER-CURRENT DECANTATION

Agitation Leaching

With the latest generation of copper–cobalt agitation leach plants in Africa, a range of advances in process and engineering designs have been developed to make operations easier and more efficient.

The most significant is the management of acid consumption and its reduction. The most beneficial is the use of pre-diluted acid for addition to the leach tanks. By reducing the local acid concentration gradient at the point of addition, significant reductions in acid consumption can be achieved (Miller, 2005a). Figure 1 shows that the actual dilution strength is not particularly important, but rather the fact that it has been diluted. To keep most common stainless steels out of their higher corrosion rate zones, dilutions to 20% or less are appropriate.

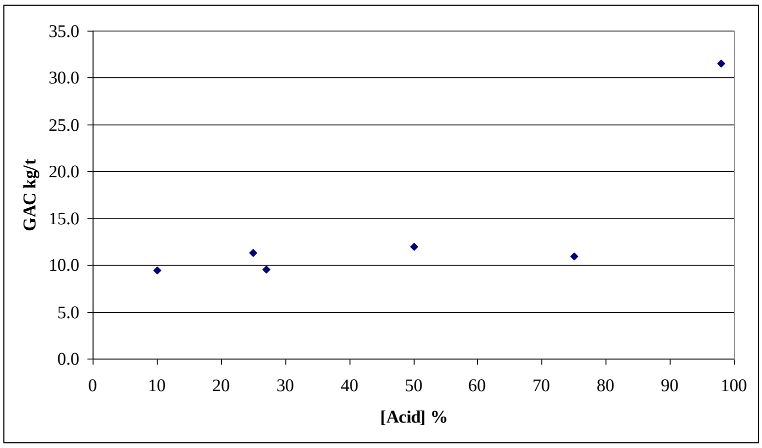

Figure 1: Effect of acid dilution on gangue acid consumption (GAC).

By changing the target pH within the leach train, further reduced acid consumption can be obtained. It is now common to have a slowly increasing pH from the first to last leach tank.

With abundant acid-leachable copper oxide minerals, it is no longer necessary to mill ores finely to achieve high leach recoveries. Coarse milling to only that size required for the target leach recovery is practiced at most of the new copper–cobalt plants (Elphinstone *et al.*, 2015). Milling to P_{80} of +200 µm is not unusual; with considerable quantities of sand, +500 µm being common. To handle these coarse slurries, special techniques are used through the leaching train, including:

- high power agitators specified for uniform suspension of 500 µm particles;
- use of sand pumps for sand transfer between stages; usually designed for 5–10% of the total slurry flow.

The engineering of the leach train has also progressed. There is now a wider appreciation of the need for a surge tank between the mill and the leach train (Elphinstone *et al.*, 2015). This removes the milling transients from the feed to the post-leach thickening stage (using either counter-current decantation (CCD) or horizontal belt filter (HBF) solid–liquid separation and washing). The leach tanks themselves are now commonly fabricated from the low-cost duplex stainless steel LDX2101. The high strength duplex allows:

- much thinner tank walls to be designed;
- the corrosion resistance negates the need for any (rubber) lining;
- the duplex structure has a high abrasion resistance, also negating the need for any wear resistant (rubber) lining;
- the stainless steel tanks do not need painting.

Overall, the use of low-alloy, lower-cost duplex stainless steel has a lower cost profile than rubber-lined mild steel tanks. Rubber lining of mild steel is no longer an attractive option due to the risks of liner failure and ultimate tank failure, as occurred at ERA Ranger operation (Energy Resources Australia, 2004).

Solid–Liquid Separation

Counter-current decantation

Thickening equipment items have undergone improvements and redesign from those available even as recently as ten years ago. The changes have meant thickeners now have enhanced capability and improved process performance. Improvements have been made, by various vendors, in thickeners that can create, transport and discharge high-density Bingham plastic slurries. This has improved the efficiency of CCD circuits with lower soluble loss from fewer units. These improvements include:

- new feed well and auto feed dilutions systems that enhance settling;
- new thickener designs for higher density, including high compression (deeper side walls) and dewatering pickets on rakes that release water from behind the pickets within the hindered settling zone;
- more robust rakes and drives for coarser solids and higher density underflows;
- use of high-shear mixers in the feed tanks to break down floccs and release entrained solutions;
- use of pump mixers (part of the high-shear mixer) to transfer CCD overflow from one unit to another, eliminating inter-stage pumps and tanks;
- an overflow header has been included to allow easy bypassing of one or even two units, on-line (John and Miller, 2014).

Overall, an enhanced potential is provided to reduce the number of CCD units, by one or two from a train of six or more used previously. The total number is still decided from the soluble loss profile of both copper and cobalt in the final CCD underflow discharge.

Slurry pumps

Improvements have been made in slurry pumps that can now handle high-density Bingham plastic-type slurries. This has improved the ability to extract higher densities from thickeners without creating pump suction cavitation. Normal slurry pumps first cavitate at the suction flange. The froth handling slurry pumps have much large suction diameters and wider impellors. The suction diameter-to-impellor diameter ratio has been shown to be a key parameter in eliminating suction cavitation with viscous non-Newtonian slurries (Burgess, 2004). Use of these pumps in plant design was pioneered at the Kinsevere operation and carried forward into the new generation of leach–CCD plants. The pump designs can add +5 to10 mass% to the pumpable percent solids. With the higher pumpable underflow densities, the CCD wash efficiency is increased, with consequently lower soluble loss and potential for fewer CCD units.

The pump materials of construction have also changed to meet the more demanding chemical environment experienced in acid leaching copper. Ultra-high chrome duplex alloys are abrasion-, corrosion- and copper cementation-resistant. Gland seal kits are readily available in stainless steel, which are combined with stainless steel shrouds to protect the cast-iron bearing housings. When combined with polyurethane elastomers, the present pumps are significantly better than the older rubber-lined pumps for difficult high-density slurry duties.

Post-leach horizontal belt filters

HBFs are also units that have evolved to address the changing needs of the copper leaching processes. The more significant improvements include:

- larger units in excess of 100 m^2;
- full stainless steel construction to resist the highly corrosive solutions;
- improved internals, including vacuum box sealing, cloth tracking, carry-belt tracking, more robust pulleys and drives, enhanced feed flocculation, feed presentation and wash water distribution;
- engineered cloth replacement systems that are easier and quicker to use;
- stainless steel vacuum pumps, needed to cope with the carryover of acid/copper aerosols from the filtrate receivers.

Most of these changes have been driven by client pressure to improve performance. Materials of construction changes have been driven by the use of recycled acidic water, for vacuum pump and HBF seal water, as part of the larger water-balance management programme.

COPPER RECOVERY CIRCUITS

Copper recovery circuits have undergone significant change from the first simple plant at Bwana Mkubwa, to the multiple solvent extraction (SX) and electrowinning (EW) circuits at the larger installations in both Zambia and the DRC.

The SplitCircuit™ Concept

An alternate approach to the conventional flowsheet was developed by Cognis, now BASF (Nisbett *et al*, 2007). The SX plant feed is split into a high-grade (HG) pregnant liquor stream (PLS) and a low-grade (LG) PLS stream that are treated separately. The split is achieved by introducing the leached pulp to a thickener (or filter) with no dilution from wash solution. The undiluted overflow or filtrate reports to the HG SX plant as the HG PLS; the thickener underflow reports to the CCD/HBF circuit, where it is washed extensively with returning process solutions. This produces an LG PLS and final CCD underflow, which reports to tailings disposal.

The SplitCircuit™ flowsheet was first introduced at the Bwana Mkubwa plant during the engineering phase of the Lonshi expansion (Miller and Nisbett, 2005). The original Bwana Mkubwa SX facility consisted of a single train, the size of which could not transfer the required amount of copper for the expanded plant. For this reason, a second SX train was constructed that allowed the separate treatment of the HG and LG PLS streams. The major benefits of the circuit concept are twofold:

- recycle of the HG raffinate with the majority of the copper and acid back to the mill/leach;
- reduction in LG PLS grade and lower LG raffinate copper concentration with lower soluble loss.

For a new project, capital constraints may dictate that only a single SX facility is affordable. In this instance, it is still possible to implement the SplitCircuit™ concept by treating the two different PLS streams utilising a series/parallel configuration in a single SX facility (Miller and Nisbett 2007). Figure 2 illustrates this concept. To date, more than ten SplitCircuit™ installations have been constructed in Southern Africa, using both concepts. A review of the costs and benefits has been covered by Nisbett *et al.* (2007, 2009).

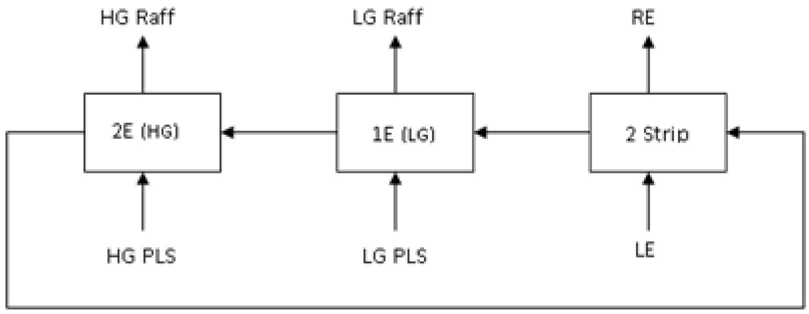

Figure 2: SplitCircuit™ in a single solvent-extraction plant.

Solvent-Extraction Plant Design

Mixer–settlers

Copper SX plant design has changed significantly since the last generation of plants were constructed. The major changes relate to improved settler feed distribution and improved entrainment management, including:

- large capacity mixer–settlers that can handle PLS flows of 2500 m^3/h or more;

- new mixer–settler designs: the older reverse flow and the newer SideFeed™ (Miller, 2006) and that from Outotec (Outotec, 2018);
- improved settler operation with better design of internals: vanes and angled picket fence for feed distribution, picket with smooth flow patterns without vortices, low turbulence organic discharge weir (Figure 3);
- lower fire risk from management of spillage, limiting aerosol production, monitoring of potential hot bearings and dead headed organic pumps;
- better layout and flexibility with on-line bypassing of entire mixer–settlers for cleaning, crud removal or descaling (Figure 4).

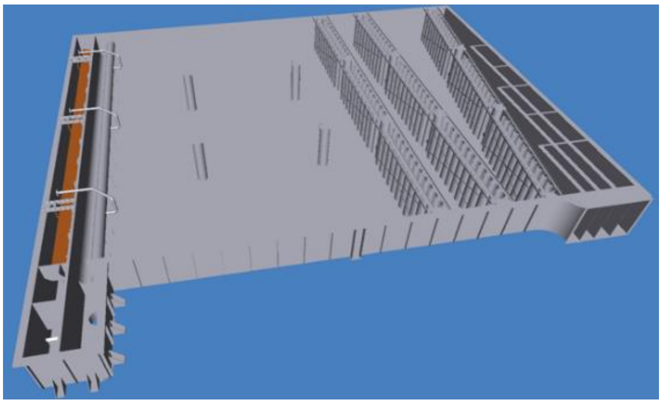

Figure 3: Improved internals in a SideFeed™ settler.

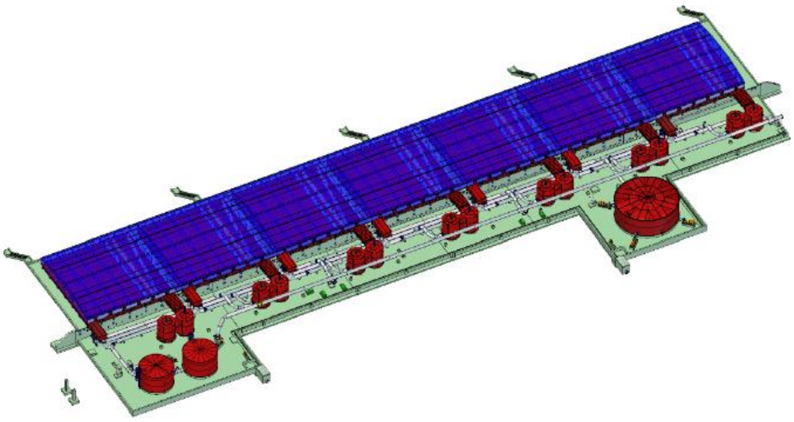

Figure 4: On-Line bypass with SideFeed™ mixer–settlers.

Entrainment control

The control of entrainment within the SX plant has been studied by a large number of workers in copper SX to try and manage not only EW current efficiency (iron concentration), but cathode corrosion (by chloride) and SX organic oxidation (by oxidized manganese). Others have focused on organic losses to advance aqueous streams with design of post SX coalescers.

Circuit design has also been improved by modelling that has shown that coalescing *before* washing has a significant and increasing benefit as the level of entrainment rises (Mackenzie and Miller, 2012). Older SX circuits using stripped organic storage have been replaced with loaded organic storage and coalescing, before any wash or scrub stage.

Contamination management, not just from entrainment control, has also progressed in understanding and management techniques to the stage that it is now an integral part of plant modelling; to understand the appropriate deportment of all contaminants of interest throughout the SX and the overall SX–EW circuit (Miller and Currie, 2014). Modelling tools now exist to quantify the evaporative loss of diluent and other more volatile components of the organic. The models show conclusively that closed-roof structures (not necessarily sealed) can reduce diluent consumption by more than 50%.

Crud extraction and treatment

There have also been developments that can improve the operability of the new SX plants. The steps revolve around increasing the effectiveness of crud extraction and making this more operator user-friendly. Crud extraction has mostly been a manual operation with significant occupation health and safety (OH&S) issues with back and arm injuries. More advanced crud extraction designs in service utilise (Miller, 2007):

- adjustable aqueous discharge weirs that allow management of the interface depth and hence the crud depth;
- integration of a crud extraction pipe as part of the organic discharge weir that can extract crud from the interface;
- permanently installed and reticulated crud extraction piping and valves that allow the operator to continuously extract crud without the need for moving of air operated pumps, or manual placement of the crud extraction nozzle;
- changes to crud treatment from pressure filtration and slow mechanical rupture techniques to the use of high-capacity continuous and robust centrifuges for crud treatment. Once these have become an integral part of the crud system it is now possible to extract and treat crud continuously to keep the settlers operating at peak performance.

Fire risk management

Management of fire risks in SX plants has had a lot of focus due to the number and severity of such fires in the last ten to fifteen years. The high flash point of the diluent used in copper SX means that the plants themselves can be *classified as a non-hazardous area.* Over 50% of copper SX plants are not classified as hazardous or hazardous-rated; however, many advances in the understanding and minimisation of fire risks are directly transferrable to new SX plants (Miller 2005b):

- use of fire plume analysis to position other assets outside the SX fire affected zone;
- understanding and implementing the standards on static electricity generation and relaxation;
- application of the appropriate hazardous area rating codes;
- attention to the detailed design of the mixer–settlers and other elements to eliminate the generation of aerosols that could lower the effective flash point even further.

Electrowinning Plant Design

The design and operation of these plants has also advanced with improved knowledge and operating experience gained from the pioneer projects in Zambia. The processes have changed, as have the equipment and operating practices.

Electrowinning process changes

The major process change has been the replacement of the direct leach–electrowin process with SX–EW plants. This has allowed the production of majority of London Metal Exchange (LME)-quality copper using stainless-steel mother-plate technology from a consistent quality electrolyte in terms of copper and acid concentrations. Plant conversions have been undertaken at three operations in Zambia and one large operation in the DRC (Mwakila *et al.*, 2008). With consistent electrolyte quality and the dimensional stability of the stainless steel plates, a combination of increased current efficiency, closer electrode spacing and higher current density has provided a pathway to significantly improved plant productivity. One Zambian project was able to double the capacity of its main tankhouse while still closing the two electro-strip sections. Another small Zambian plant, using leach and electrowinning of zinc, converted to copper SX–EW with good financial results.

Other cost savings have been realised with near zero recycle of off-specification copper back to the smelter for remelting and recovery in the electrorefinery. Further benefits have also been evident with the elimination of the starter-sheet technology previously used:

- the elimination of a large number of operator tasks with high injury risks from manual stripping of copper from the mother plants;
- much less plant spillage and corrosion without the need for 'wet flapping' of partially grown starter-sheet deposits.

With the high levels of cobalt in the Copperbelt ores, a build-up of cobalt in the electrolyte can occur from PLS entrainment in the loaded organic. The effect of this was first noticed in a significant reduction of the output voltage of the rectifier. Copper was still being plated at the design rate, but the cell voltage had dropped significantly. Subsequent literature search showed that this was due to the high concentration of cobalt in the electrolyte (Miller, 2011a). An additional benefit of the reduced cell voltage is a similar reduction in the total power used for copper deposition.

Solvent-extraction process changes

Some changes to the SX plant design were needed to address the specific needs of stainless-steel mother plate EW. All changes related to the control of entrainment of various contaminants into the electrolyte, via entrainment of PLS into the electrolyte, via the loaded organic or direct entrainment of SX organic in the strong electrolyte (Miller, 2011b). The key issues are:

- transfer of iron via both chemical and entrainment;
- the transfer of manganese via entrainment;
- the transfer of chloride in southern Africa is not an issue due to very low background chloride in all surface and subterranean waters;
- the entrainment of SX organic in the strong electrolyte.

Various conventional processes have been applied to minimise these transfers:

- improved settler performance with better and more consistent feed distribution (Miller, 2007);
- use of loaded organic and strong electrolyte coalescing;
- use of a wash/scrub stage to both dilute the manganese and iron physical transfer, and to chemically scrub the iron from the loaded organic;
- use of dual media filters to coalesce organic in the strong electrolyteu
- use of polishing EW cells as a final capture in 20% of the cells; while the other 80% of cells are kept organic-free. The technique has recently been supplemented by a new method of continuously decanting the separated organic from the tops of the cells.

Equipment changes

The major equipment changes have been associated with the change to stainless-steel mother-plate technology. This has involved the concurrent changes to supporting equipment and hardware:

- change from cast antimony–lead anodes to lead–calcium–tin alloy to facilitate operation at higher current densities;
- universal use of polymer concrete EW cells;
- manufacture and installation of much larger rectifiers and bus bar systems to carry the higher currents being used;
- with larger and longer EW cell lines, higher speed remote-controlled cranes can increase harvesting productivity;
- electrolyte temperature management can be an issue with the closed circuit mill–leach–SX–EW circuits. The circulating PLS can reach temperatures of over 40°C. There is a large amount of the EW energy dissipated as IR losses into the electrolyte. Cooling of the electrolyte is needed to prevent temperatures in excess of 50°C in the spent electrolyte. Inclusion of indirect electrolyte cooling has been necessary on most of the agitation leach plants;
- heating of the cathode wash water improves washing efficiency in the stripping activity. The energy input is considerable and consequent costs of electric or diesel sources. One operation has used an innovative heat pump arrangement to both cool the electrolyte and provide heating

of the cathode wash water. The cost of the installation is considerable, but the saving in energy costs is an attractive investment;

- larger tankhouses (with +100 cells) need to have an almost continues daily activity for cell clean-out. A two-cell shorting frame allows both cells to be cleaned and maintenance of the inter-cell bus bar and capping boards. To facilitate the clean-out activity, a central positive displacement pump has been provided with a reticulated suction pipe manifold. Only a short hose is needed to service, say, five cells from any single permanent suction connection point. Considerable OH&S benefits and labour reduction can be achieved.

Operating changes

Significant operating changes have been made to EW plants, compared with previous African practice. Most are related to the use of stainless-steel mother plates while others relate to harvesting and interactions with the SX plant.

The most significant change is the harvesting method. The starter sheets in a cell were traditionally harvested by removing one third at a time (every third) and replacing with new starter sheets. A full cell was harvested using three separate removals of every third cathode. The harvest then moved on to the next cell. The starter sheets had the copper growth morphology 'set' from the one or two days' deposition on the Ti mother plates. Further copper growth reinforced the starting morphology.

In contrast, stainless-steel mother plates are harvested every third, but each third (A, B or C cathodes) are harvested all round the tankhouse over a period of two days, *before* the harvesting of the next third of the cathodes - the ISAPROCSSS method (Miller *et al.*, 2014) has shown that the harvesting method is one of the most significant factors in the copper quality. The growth morphology can change depending on the number, level and timing of the increased current density on the remaining cathodes when the harvested cathodes are out of the cell. Any other harvesting method in general produces poorer copper with more nodules and higher levels of sulphur.

High current density operation at more than 350 A/m^2 is now common in many tankhouses. There is a higher risk of nodule formation and lower product quality, but this is offset by the increased productivity of the tankhouse. The first generation of EW plants used a design current density of 200 A/m^2. This has now increased to 320–350 A/m^2. Some of the older plants are now operating at more than 50% above original design. One of the more recent improvements that has assisted this change is the use of a neutral polyacrylamide flocculant as the main growth modifier. Addition of the flocculant to the high Eh electrolyte provides the conditions for acid activate the polyacrylamide (Fabian *et al.*, 2007) and shown the benefits of such acid activation in growing nodule-free copper.

WATER BALANCE AND REUSE

One of the greatest areas of improvement in process and engineering design is that of improved water balance management. Previous agitation-leach projects were nett generators of water for disposal. These waters could only be partially recycled from the tailings facility. Excess water had to be disposed of – generally by evaporation. The newer copper–cobalt projects in south central Africa have developed a range of techniques to reverse the water balance from positive output (excess water in the system) to a negative output (requiring water input to the system). The overall water usage is reduced considerably compared with those needing to evaporate excess water. The changes include fundamental new circuits and new equipment, along with major improvements in 'standard' equipment performance levels.

Milling in Raffinate

The milling in acidic raffinate (MIR), with stainless steel mills, for agitation-leach plants, has fundamentally changed the water balance and improved acid consumption and leach recovery (Miller and Kendall, 2013). The largest input in the water balance is the moisture brought in with the milled ore. One method of achieving a negative water balance is to mill in recycled acid raffinate. The practice has been used in the Florida phosphate industry for many years (Miller and Kendall, 2013). Mills there are typically protected with rubber lining due to the relatively mild corrosion rates experienced; however, the presence of any copper in the recycled raffinate stream leads to extreme corrosion rates from the copper–iron cementation reaction.

The practice needs a stainless steel (or stainless steel-lined) mill with ceramic, pebble or corrosion-resistant grinding media to be fully effective. The strong operating cost drivers for the process resulted in the first installation at Sepon (Baxter *et al.,* 2004). The benefits to the water balance are significant as no new water is added to the grinding step, other than the moisture in the ROM ore. Further installations were made at Kinsevere in 2008 and Mutanda Mining in 2012, 2104 and 2016 (Elphinstone *et al.,* 2015). The advent of the low-alloy duplex stainless steel LDX2101 has provided the high strength required to manufacture mill shells and heads. Mills up to 8 MW are now in service, with both SAG and ball mills being used.

With the elimination of the water associated with the milled ore, there is a nett output of water in the solids placed in the tails storage facility (TSF). Providing that the other water inputs are managed, there is a nett negative water balance and more water is needed in the circuit to provide the TSF losses in solids and evaporation. The negative water balance has major positive implications:

- major recycle of SX plant raffinate to the mill – with consequent savings in reagents;
- reduced acid consumption from a combination of increased recycle in the raffinate, higher raffinate total dissolved solids, with lower ore acid consumption from the higher total sulphate, and elimination of excess raffinate sent to neutralisation;
- reduced neutralisation plant size and operating cost from the significantly reduced total solution discharge from the process
- elimination of secondary TSF water treatment to allow offsite discharge of the excess volumes. Particularly in high rainfall areas this has a large environmental and operational risk reduction;
- any 'new' water input required, is mostly applied as part of the solids washing steps, which results in lower soluble losses (of acid in particular).

The MIR process also has some side benefits that were not readily apparent in the first installations. The milling activity needs to be conducted at the leaching pH/acidity to prevent precipitation of copper. Once this control is incorporated in the design, the milling activity promotes the leach kinetics substantially, probably by a mechanical activation mechanism (Miller and Kendall, 2013). Leaching in the mill plus leaching in the pre-leach storage tank can reduce the total leach tank volumes required for the same target extraction.

Water Substitution by Recycled Solutions

Once a MIR circuit is chosen, the other major water inputs to the plant are: reagent make-up, secondary flocculant dilution, HBF seal and cloth wash waters and slurry pump-gland service water. The initial reagent make-up water should always be with fresh/raw water; however, the other services can be substituted by recycled SX raffinate or TSF return water:

- gland service for pumps require only a low-cost stainless-steel gland kit along with corrosion resistant tanks, pipes and gland water pumps;
- secondary flocculant dilution has been shown to be viable with SX raffinate;
- HBF cloth wash and belt seal are readily accommodated with stainless-steel wetted/splashed components on the filter;
- vacuum pump seal water can also be supplied by SX raffinate with a stainless-steel vacuum pump. Both the HBF and the vacuum pump should be corrosion-resistant stainless steel for the post-leach filtration duty.

Use of Acid Tails Storage Facility
Older plants neutralised their leach tails for impoundment in a conventional TSF. By lining the TSF using the methods developed for acid heap leaching, it is possible to store acidic tails that have not been neutralised. The initial increased capital cost of the lining is more than offset by the eliminated capital for the neutralisation and limestone milling plants and of the annual operating cost reductions for lime and limestone:

- recycle of acidic solutions leads to reduced overall acid consumption and increased copper leach recovery from continued leaching in the TSF;
- elimination of the need for lime or limestone to conduct the neutralisation;
- creation of a renewable resource in the TSF where the residual metal values have been retained.

Overall, there is also a significant reduction in the project carbon footprint:

- reduced mobile equipment fuel consumption: mining, transport and processing of limestone;
- no carbon dioxide effluent from lime burning or transportation of lime;
- reduced power consumption with reduced power station emissions.

OVERALL PLANT IMPROVEMENTS

Several developments in plant layout and design increase the operability and utilisation of the overall plant. Plant utilisation in the milling and leaching side is often lower than in the solution treatment, SX and EW plants. A number of dynamic plant models have shown the significant benefit to be gained by having large solution storage volumes between the mill–leach–CCD part and the SX–EW part. Pond sizes of 24 to 72 h are needed. The lesser volume would be for a heap leach (with its simpler dynamics), while the greater time was required for a project with pressure acid leaching and sequential SX recovery for copper, cobalt and nickel. The more complex each of the plant sections are, the greater the volume of surge is needed. The largest volumes are needed to separate two process plant sections that feed each other, e.g., the mill–leach–CCD feeds SX, and SX raffinate is used in the mill and CCD sections.

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REFERENCES

Baxter, K., Dreisinger, D., Pratt G. (2004). The Sepon copper project: design of a flowsheet. *Proceedings Hydrometallurgy 2003*. The Minerals and Metals Society, Vol 1. Warrendale, PA. pp. 1487–1502.

Burgess, K.E. (2004). Developments in the pumping of mineral froths and non-Newtonian slurries. Weir Warman Ltd.

Elphinstone, M., Miller, G., Kendall, K., Kumwenda, E., Gross, J., du Preez, T. (2015). Milling in acid-copper raffinate at the Mumi Phase 4 operation. *Proceedings Sixth International Conference on Semi-Autogenous & High Pressure Grinding Technology*. Canadian Institute of Mining, Metallurgy and Petroleum, Montreal.

Energy Resources Australia (2004). Leach tank incident update. Press release, http://www.energyres.com.au/documents/20140326_leach_tank_update_media_release_FINAL.pdf [accessed 24 March 2016].

Fabian, C.P., Ridd, M.J., Sheehan, M.E. (2007). Assessment of activated polyacrylamide and guar as organic additives in copper electrodeposition. *Hydrometallurgy,* 86, 44–55.

John, L.W., Miller, G.M. (2014). State of the art of solvent extraction and electrowinning design. *Proceedings ISEC 2014, 20th International Solvent Extraction Conference*, Würzburg, pp. 609–615.
Mackenzie, M., Miller, G.M. (2012). Uranium solvent extraction plant designs- where does copper come into it? *Proceedings ALTA Gold-Uranium Conference*. ALTA Metallurgical Services. Melbourne.
Miller, G.M. (1994). Materials handling. In: *Advanced Coal Preparation Monograph Series: Volume II: Materials Operations,* Swanson, A.R., Partridge, A.C. (eds.) 1st edn. Australian Coal Preparation Society. Brisbane, QLD. pp 1–55.
Miller, G.M. (2001). *Site visit report to Bwansa Mkubwa.* Internal Report. Sinclair Knight Mertz. Brisbane.
Miller, G.M. (2005a). Analysis of leaching data: methods and interpretation. *Proceedings First Extractive Metallurgy Operator's Conference.* Australasian Institute of Mining and Metallurgy. Brisbane.
Miller, G.M. (2005b). SX fires – their initiation and propagation. *Proceedings ALTA SX Fire Protection Summit*. ALTA Metallurgical Services, Melbourne.
Miller, G.M. (2006). Design of mixer-settlers to maximise performance. *Proceedings ALTA Copper 10*. ALTA Metallurgical Services, Melbourne.
Miller, G.M. (2007). SX contactors for the future. *Proceedings ALTA Copper-11*. ALTA Metallurgical Services, Melbourne.
Miller, G.M. (2011a). Contamination management in solvent extraction plants. *Proceedings ISEC 2011*. Gecamin, Santiago. Paper 1–28.
Miller, G.M. (2011b). Methods of managing manganese effects on copper solvent extraction plant operations. *Solvent Extraction and Ion Exchange,* 29 (5–6), 837–853.
Miller, G., Clark, R., Williams, S., Heferan, G., Aslin, N. (2014). Selection of copper electrowinning harvesting methods and impacts on copper product quality. *Proceedings Hydrometallurgy Conference 2014*. Vol. II. Canadian Institute of Mining, Metallurgy and Petroleum, Montreal. pp. 115–130.
Miller, G., Currie, B. (2014). Integrated design considerations of copper solvent extraction and electrowinning plant to maintain high quality product quality. *Proceedings Hydrometallurgy Conference 2014*. Vol. II. Canadian Institute of Mining, Metallurgy and Petroleum, Montreal. pp. 339–352.
Miller, G.M., Kendall, K. (2013). Milling in acid-copper raffinate at the Mumi Operation DRC. *Proceedings ALTA Cu-Ni-Co Conference.* ALTA Metallurgical Services, Melbourne.
Miller, G.M., Nesbitt, A. (2005). Decreasing operating costs and soluble loss in copper hydrometallurgy with use of innovative solvent extraction circuits. *Proceedings First Extractive Metallurgy Operator's Conference*. Australasian Institute of Mining and Metallurgy, Brisbane.
Miller, G.M., Nesbitt, A. (2007). Use of Split Circuit™ SX plants for high copper recovery and low operating costs. *Proceedings ALTA Copper-11.* ALTA Metallurgical Services, Melbourne.
Mining Data Online (2018). Tenke Fungurume Mining. http://miningdataonline.com/property/302/Tenke-Fungurume-Mine.aspx#Mining [accessed 21st March 2018].
Mwakila, B., Silwamba, R., Miller, G., Chisakuta, G.C. (2008). Improvement in copper and cobalt production due to inclusion of solvent extraction of copper at Mopani Copper Mines Plc's Nkana cobalt RLE plan*t. Proceedings of ISEC 2008.* Canadian Institute of Mining, Metallurgy and Petroleum, Montreal. pp. 145–150.
Nisbett, A., Baxter, K., Marte, K., Urbane, M. (2009). Flowsheet considerations for copper-cobalt projects. *Proceedings Base Metals Conference.* Southern African Institute of Mining and Metallurgy. Johannesburg. pp. 139–152.
Nisbett, A., Feather, A., Miller, G. (2007). Implementation of the Split Circuit™ concept into copper agitation leach plants. *Proceedings HydroCopper 2007, IV International Copper Hydrometallurgy Workshop*, Gecamin, Santiago. pp. 185–190.
Outotec (2018). VSF. http://www.outotec.com/products/solvent-extraction/vsf-x-solvent-extraction-plant-unit/ [accessed 21st March 2018].
Sandvik (2018). Stationary hybrid crushers. https://www.rocktechnology.sandvik/en/products/stationary-crushers-and-screens/stationary-hybrid-crushers [accessed 20th March 2018].