Improved Cleaner Circuit Design for Better Performance Using the Jameson Cell

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ABSTRACT

In today's operating environment many conventional cleaner circuits struggle to produce final grade concentrate with acceptable levels of non-sulfide gangue and/or penalty elements. This is primarily due to poor selectivity and the entrainment of gangue, and is further exacerbated by the processing of lower grade ores with more complex mineralogy that require finer grinding for liberation. In new concentrators, the standard approach to cleaner circuit design is to define the number of stages of mechanical cells required to achieve the desired concentrate grade. Residence time is the primary factor to size cells and to determine the number of cells required to attain target recovery. While it is required for recovery, a bank of mechanical cells is not the ideal solution to maximise concentrate grade. Relatively coarse bubble size means slow flotation of fines, requiring long residence times. The combination of long residence times and no froth washing means higher entrainment as the pulp becomes more barren and froth stability decreases down a bank.

In recent years, the Jameson Cell technology has been retrofitted into a number of concentrators around the world to solve both cleaner circuit capacity and concentrate grade issues. Jameson Cells have been installed at the head of conventional cleaner circuits to produce final grade concentrate in a single step of flotation using a single cell (referred to here as 'cleaner scalping' duty). The experience gained from these installations has provided the platform for the design of improved and simpler cleaner circuits that will perform better and be more robust to operate.

This paper analyses traditional cleaner circuit designs and explains the philosophy behind new hybrid cleaner circuits, which use Jameson Cells to produce final concentrate and mechanical cells for a 'cleaner scavenger' duty. The advantages of the new cleaner circuit design are demonstrated by a case study from an operating plant. Engineering studies show that the better metallurgical performance can be achieved with less equipment than conventional cleaning designs, reducing capital cost, operating cost, and with more than 30 per cent energy savings.

Finally, the paper describes simple modifications to the standard laboratory flotation test procedures which accurately simulate this new cleaner circuit using routine equipment.

INTRODUCTION

Depletion of the world's mineral resources imposes great pressure on the efficiency of modern concentrators. The combination of lower head grades, more complex mineralogy and environmental requirements places new demands on concentrate quality, both in terms of concentrate grade and the need to remove deleterious elements such as arsenic, fluorine, mercury and uranium. Regrinding of the rougher concentrate is increasingly required to liberate the valuable minerals sufficiently to produce a saleable concentrate. The finer the grind, the more difficult is subsequent flotation separation in the cleaning circuit to produce the desired concentrate quality. Despite these increasing challenges, there does not appear to have been significant design changes in cleaner circuits in recent decades. Most new plants today, particularly in Australia, are still designed predominantly with conventional mechanical cells for cleaning.

The primary purpose of a flotation cleaning circuit is the separation of valuable (hydrophobic) minerals from non-valuable minerals. Non-valuables include hydrophilic gangue, mildly hydrophobic minerals such as iron sulfides, and minerals locked in composite particles. In industry, cleaning is commonly achieved with multiple stages of counter-current banks usually consisting of mechanical flotation cells. However, in some recent brownfield projects, cleaning circuit modifications have been required to either increase capacity,

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to improve recovery, or to increase concentrate grade and remove penalty elements. These upgrade projects have been an opportunity to develop and demonstrate alternative approaches to cleaning circuit design. This includes using froth washed cells such as columns or Jameson Cells, and the use of small bubble size and very high intensity mixing, such as the Jameson Cell, to increase the flotation rate of fine particles. Combining these advantages of high flotation rate and froth washing with long residence times possible in mechanical cells has developed hybrid circuits that combine the benefits of both technologies in more efficient, more effective, lower energy circuits. Having been developed to improve existing circuits, it is now clear these circuit concepts offer a step change improvement for the design of new circuits.

In conventional mechanical flotation cells, the recovery to concentrate by entrainment can be described by a size dependent parameter (ENT_i) that relates the recovery by entrainment of particles in size fraction i ($R_{ent,i}$) to water recovery across the cell (R_w) as follows (Johnson, McKee and Lynch, 1974; Savassi *et al*, 1998):

$$R_{ent,i} = ENT_i \cdot R_w$$

In mechanical cells, it is necessary to reduce water recovery in order to lower entrainment recovery – this can be achieved by reducing water recovery through feed dilution while maintaining valuable mineral recovery if there is sufficient residence time in the flotation cell or bank. In froth washed systems, such as columns and Jameson Cells, the entrainment factor (ENT) is reduced by froth washing with a positive downward water bias.

The Jameson Cell is a high intensity flotation technology jointly developed in the mid-1980s between Mount Isa Mines (MIM, now Glencore) and Professor Graeme Jameson from the University of Newcastle. What started as a research project to improve the sparger design in the column cells installed in MIM's zinc cleaner circuit, culminated in the development of a completely different bubble-generation device called a downcomer. When it was discovered that, in addition to being a bubble generation device, bubble-particle collisions also occurred inside the downcomer (Harbort, Manlapig and DeBono, 2002), it became apparent that the large residence time and hence, large volumes required for the collection zone in column cells was not needed. This meant that the downcomers could be placed in much smaller tanks, to achieve the same or better metallurgical results. This is shown graphically in Figure 1 (Jameson, 1988).

Since its commercialisation in 1989, the Jameson Cell has undergone two decades of development in operating plants, with the latest Mark IV designs being highly reliable and operable. Figure 2 shows the development path of the technology in that time frame. Modern designs are fully instrumented and require very little maintenance due to significant design improvements to the downcomer, the unique feature of the technology. The technology has been 'tried and tested', and installed in many different duties but in recent years it has been almost exclusively used in cleaner circuits. The ability of the Jameson Cell to produce final grade concentrates in a single stage of flotation, through fine bubble generation, intense bubble-particle contact and the use of froth washing to minimise entrainment, has seen it being successfully retrofitted into a number of concentrators around the world to add cleaner capacity and/or solve concentrate grade issues (Araya *et al*, 2013).

This paper applies the developments from these brownfield installations to provide a new design basis for improved
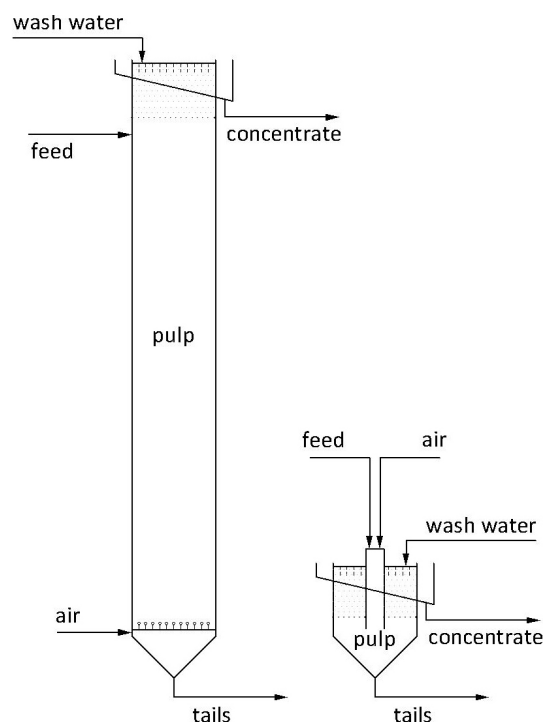

FIG 1 – Comparison of the size of a column cell (left) to a Jameson Cell (right). Reproduced from Jameson (1988).

'greenfield' cleaning circuits. The new concept is for hybrid cleaning circuits that are simpler, cheaper, and more robust, and that provide better grade/recovery performance. The feature of the improved 'hybrid' circuit is the use of Jameson Cells to control grade and produce the entire plant final concentrate, and mechanical cells for cleaner scavenger duty to provide overall cleaner circuit recovery.

The operation of such a circuit will be demonstrated in a case study from a recent installation. Engineering considerations such as circuit residence time, footprint and installed power of this new cleaner circuit compared with traditional 'standard' designs, to show that the better performance is accompanied by 30–40 per cent reductions in equipment footprint and energy. The methodology to accurately simulate this circuit design using standard laboratory equipment is described.

DESIGN AND PERFORMANCE OF CONVENTIONAL CELL CLEANING CIRCUITS

The conventional approach to development of cleaner circuit flow sheets is to conduct batch flotation tests to define flotation kinetics and the number of cleaning stages required to achieve the desired concentrate quality. This work should be carried out in conjunction with mineral liberation and regrinding studies. Usually, locked cycle tests are performed to simulate the entire concentrator design in closed circuit with circulating loads. This determines stream flow rates and scale-up of cell capacities. Copper and lead cleaning circuits typically employ two to three stages of counter-current cleaning. Generally, the finer the feed and the lower the head grade, the greater are the number of cleaning stages required to achieve product grade, since separation becomes less effective and entrainment more prevalent. For example, at Glencore's McArthur River and MMG's Century Mine operation, the feed size to the cleaning circuit is around D_{80} of 6–8 microns, requiring five or more cleaning stages to produce the desired zinc concentrate quality. Generally, residence time is the primary factor used to determine the number and size of flotation cells needed for target recovery. But in the last cleaning stage carrying capacity
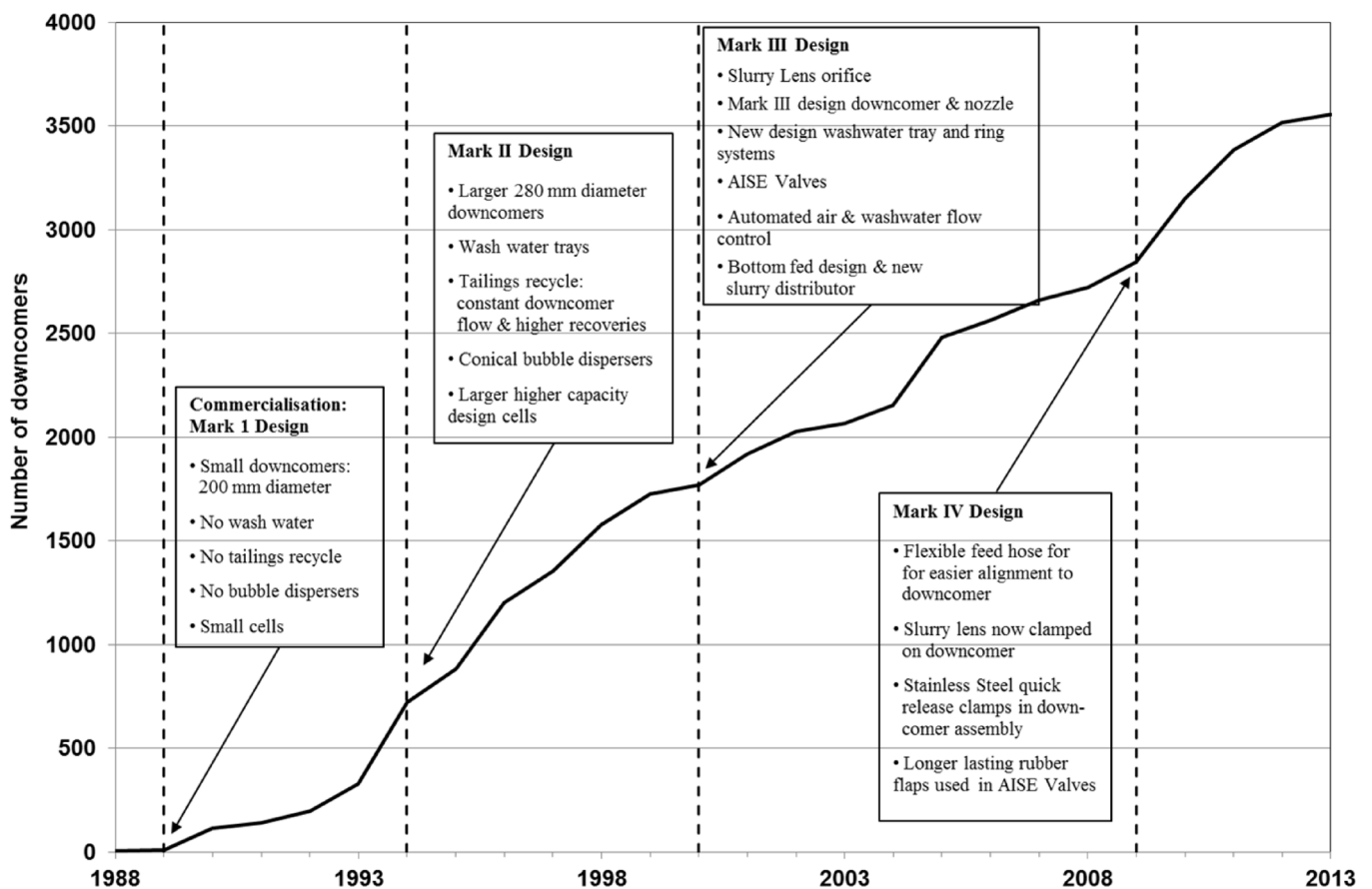
FIG 2 – Development path of the Jameson Cell technology over two decades.

(bubble surface area available) and lip loading (mass flow rate of concentrate per concentrate lip length) may be governing design parameters. In turn, lip loading and carrying capacity are primarily determined by particle size and density, so 'rules of thumb' developed for coarse flotation will be incorrect for finer flotation.

In many plants, issues with conventional cleaner circuits usually relate to either insufficient capacity (and hence recovery), or inability to consistently achieve final grade quality. The former may be due to under-design of the original circuit and/or increased loading as a result of the common practice to 'push more tonnes'. In these cases, performance is very sensitive to feed grade and solids content. Upgrade ratios of valuable minerals generally decrease in each successive stage, hence the need for multiple stages of cleaning (although this also depends on other flotation factors such as ore characteristics, chemistry and particle size). Performance also depends on how effectively operators can make use of the normal flotation controls, ie dart valves for froth depth and valves for air flow rate, to control froth drainage and mass pull, particularly at the last stage of cleaning. Ideally, controls would be available for every cell but this is seldom the case in multistage cleaner circuits. Even in plants with conventional trough cells, level control is across an entire bank and air addition is controlled by a single automated air valve with manual butterfly valves to each cell, which are typically difficult for an operator to access. In any case, banks of conventional cells are not the most efficient way to produce both high-grade and high recovery. The relatively large bubble size and low mixing intensity means relatively slow flotation rates, especially for finer particles. High recoveries can be still be achieved by long residence times, but this is at the expense of grade, since the long flotation times without

froth washing means high entrainment. Columns offer the benefit of froth washing to improve grade, but their low mixing intensity (and often the large bubble size) means slow flotation rates and slow recovery of fines.

AN IMPROVEMENT ON CONVENTIONAL CELL CLEANER CIRCUITS – JAMESON CELL CLEANER SCALPING

The above discussion suggests that the best solution may require a combination of technologies. Producing high-grade concentrates (particularly from finer streams) needs concentrate to be froth washed. To be practical, froth washing needs to be applied in a small area – so it needs high flotation rates and shorter residence times. Achieving high flotation rates (particularly for fines) needs small bubbles and intense mixing. But achieving high recovery of the slowest floating particles needs long residence times. No technology has demonstrated the ability to achieve all of these simultaneously. However, by combining the best features of Jameson Cells with mechanical cells, it seems possible to design circuits to achieve higher grade (from fully froth washed concentrate) with high recovery (from adequate residence time in mechanical cells), in an overall smaller installation (from fast flotation rates of small bubbles and intense mixing in the Jameson Cell downcomer).

These design concepts were tested on plant cleaner feed streams in several existing operations. It has been consistently shown that Jameson Cells can produce a higher grade in a single stage compared with multiple (typically two or three) stages of conventional cleaning. An example is shown in Figure 3. The data for the Jameson Cell and the existing plant circuit was collected at the same time during a recent pilot
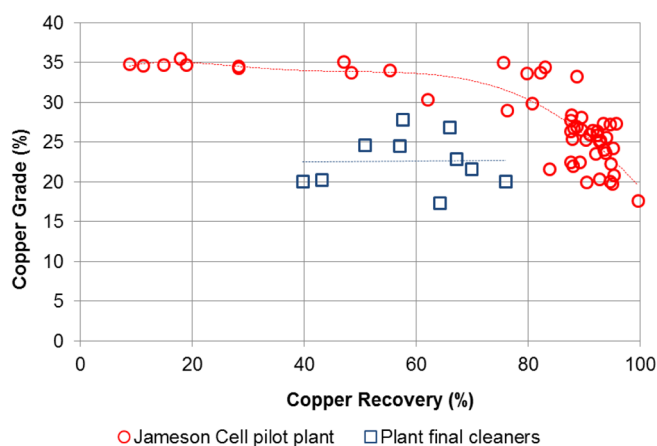
plant campaign. The Jameson Cell is clearly more selective and operates on a superior grade/recovery curve. It produces a copper concentrate at 35 per cent Cu grade (the ore contains chalcopyrite and secondary copper minerals) in a single stage of flotation, whilst the operating plant cannot consistently produce a final concentrate above 28 per cent Cu using two stages of cleaning in conventional mechanical cells.

Since the increasing application in base metals around 2005 (Young *et al*, 2006), Jameson Cells have been successfully retrofitted to solve capacity and grade issues in a number of copper operations around the world (Araya *et al*, 2013). The referenced brownfield projects and the reasons for Jameson Cell inclusion are as follows:

- PanAust's *Phu Kham* operation in Laos – to increase cleaner circuit capacity (Bennett, Crnkovic and Walker, 2012)
- Newcrest's *Telfer* operation in Western Australia – to reject non-sulfide gangue (NSG) and improve cleaner circuit recovery (Seaman *et al*, 2012)
- Barrick's *Lumwana* operation in Zambia – to reduce uranium mineral entrainment allowing the plant to consistently produce a saleable concentrate below acceptable limits (Araya *et al*, 2014)
- OZ Mineral's *Prominent Hill* operation in South Australia was a new plant in a greenfield project where fluorine was identified to be an issue during the development phase of the project (Barns, Colbert and Munro, 2009).

At these sites, Jameson Cells were installed at the head of the existing conventional cleaner circuit. The Jameson Cell treats the cleaner feed stream producing a very clean high-grade final concentrate. The tailings from the Jameson Cell then go to a cleaner section with conventional mechanical cells, which will now treat a lower grade feed. Because the mineral load to these cells is now significantly lower they can be 'pulled' much more slowly allowing better froth drainage. The feed to the mechanical cells is now at a lower density which aids separation efficiency and reduces entrainment. The concentrate from the final stage of mechanical cell cleaning is combined with the concentrate from the Jameson Cell to produce the overall plant final concentrate. A review of the Jameson Cell performance in these plants showed that:

- The actual unit recovery of the Jameson Cell was generally higher (typically 60 to 80 per cent) than the original design (typically 50 per cent). Maximum recovery was found to be controlled by mineralogy and the amount of liberated mineral together with the quantity of fast-floating particles in the feed, rather than any machine limitations.

- The 'shape' of the selectivity curve between valuable mineral and gangue is dictated by liberation. When treating liberated streams (ie after regrinding), high rejection of gangue (>90 per cent) can be achieved at a valuable mineral recovery as high as 80–90 per cent.
- Carrying capacity was never an issue due to the low mass pull requirement as the upgrade ratios are generally high in this duty (typically greater than five). The tailings recycle designed into the Jameson Cell allows it to handle any large fluctuations in feed and the short 'residence time' in the cell (less than three minutes) allows it to respond quickly to both plant disturbances or changes in process variable settings by operators.
- The Jameson Cell is very forgiving to changes in feed grade and (slurry) density. The operation is robust and the cells require little maintenance.

The performance of the conventional cleaner circuits downstream of the Jameson Cell was found to vary widely across these different sites. A summary at each operation is as follows:

- *Phu Kham* – the Jameson Cell achieved its role in adding sufficient cleaner circuit capacity. After the Jameson Cell was installed, the improved performance of the cleaner circuit increased the overall plant copper recovery by 0.8 per cent (Bennett, Crnkovic and Walker, 2012).
- *Telfer* – the addition of the Jameson Cell increased the copper recovery in the overall cleaner circuit from approximately 85–95 per cent. There was also an overall net benefit in concentrate quality. Figure 4 compares the NSG in the final plant concentrate before and after the Jameson Cell installation. Clearly, the plant is able to produce a cleaner concentrate lower in NSG after Jameson Cell installation (also shown for comparison is the cumulative frequency plot for NSG in the Jameson Cell concentrate). However there was no noticeable difference in the overall copper grade in the plant final concentrate. This is because the Jameson Cell at the head of the circuit recovers most liberated copper at a higher grade, allowing the recleaner cells to recover a larger fraction of the composite particles. That is, the plant is converting the increased cleaning power to higher recovery rather than higher grade.
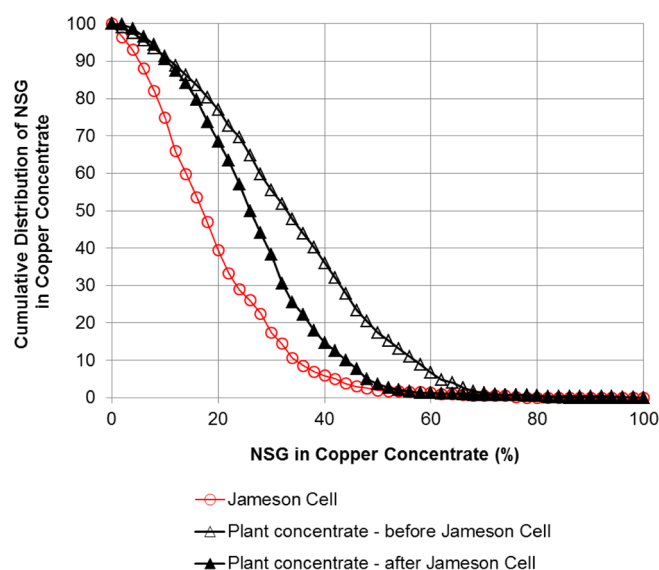

FIG 4 – Cleaner circuit performance at Telfer showing non-sulfide gangue in Jameson Cell concentrate and final plant concentrate before and after installation of the Jameson Cell.

- *Lumwana* – soon after commissioning, the scalper Jameson Cell was switched from a scalping duty to instead replace the plant conventional recleaner bank. This chance was due to equipment constraints and bottlenecks elsewhere in the circuit. The change was successful and the plant now consistently produces on-specification concentrate, eliminating the previous need for concentrate blending. While the Jameson Cell was originally employed to solve a concentrate quality issue at Lumwana, its installation and other initiatives undertaken by site personnel over the past two years has seen recovery increase at the plant of 1.3 per cent (Araya *et al*, 2014).

- *Prominent Hill* – the Jameson Cell produces a high-grade copper concentrate and is very effective in rejecting entrained gangue thereby minimising fluorine levels. The three stages of mechanical cell cleaning produces a lower grade copper grade with higher levels of fluorine (as expected). However, the Jameson Cell contributes a greater proportion (more than the original design) to the final concentrate than the final stage of the conventional cleaners, so the overall final concentrate is still within acceptable fluorine level.

PROGRESSING TO AN OVERALL NEW CLEANER CIRCUIT DESIGN

It is well known that froth washing is the most effective method for reducing the recovery of gangue by entrainment, particularly in cleaning circuits. It is therefore logical that all streams reporting to final concentrate should employ a froth washing type of machine, and the circuit should be designed to maximise overall cleaner circuit recovery. Froth washing is not usually used in mechanical cells. This is partly due to practical constraints – it is difficult to design effective froth washing systems to fit on top of the cells; and the cells do not generally provide a deep and stable enough froth bed to sustain froth washing. Furthermore, the slow flotation rates (due to large bubble size and less intense mixing) means long flotation times and a large surface area required to achieve recovery. To froth wash such a large area requires an impractical amount of water that would overload the rest of the circuit.

The examples described clearly indicate that the addition of cleaner scalper Jameson Cells to these previously all-mechanical cell cleaner circuits was beneficial to the metallurgical performance. The cleaner scalper cells were able to produce a very clean concentrate at relatively high stage recoveries (typically 50–70 per cent), reducing the valuable mineral load on the subsequent mechanical cleaner cells. Final stage concentrate from mechanical cells was higher in NSG content than before the installation of the scalper cells due to the mechanical cleaning circuit receiving a lower grade feed from the Jameson Cell tails. However, the net effect of the new circuit design is an overall reduction in entrainment to the final concentrate and an increase in the overall cleaner circuit recovery.

There is room to further improve these circuit designs to achieve maximum entrainment rejection. At Lumwana, after the installation of the cleaner scalper, further rejection of fine liberated non-floating gangue particles was sought. Since the majority of this gangue was reaching final concentrate from the mechanical recleaner cells, the decision was made to switch the duty of the Jameson Cell from a scalper to a recleaner. This improved overall gangue rejection as the Jameson Cell now produces the entire plant concentrate. In circuits where the first (and/or second stages of cleaners) are capacity limited (eg launder, froth surface area or residence time), this alteration would be unsuitable as it would impact (reduce) the resulting overall cleaner circuit recovery.

Figure 5 proposes an improved cleaner circuit design to combine and maximise the advantages of both Jameson Cells and mechanical cells. It comprises a Jameson Cell cleaner scalper, a single bank of mechanical cells for scavenging cleaner tailings for high recovery, and a second Jameson Cell for final cleaning. The first Jameson Cell recovers the fast floating liberated minerals and produces a high-grade concentrate. It also acts as a buffer in the overall cleaner circuit as it is designed with sufficient capacity to handle varying mass and mineral loads from the rougher/scavenger cells. A Jameson Cell will typically recover 50–70 per cent in a single pass. This recovery range is typical in the final cleaning stage, supported by a sufficient circulating load to provide a high overall circuit recovery. In this design, the circulating load is supported by the mechanical cleaner scavenger cells, which can provide the long residence time for ultimate recovery, while sending the (relatively low-grade) concentrate to another Jameson Cell rather than directly to final concentrate.
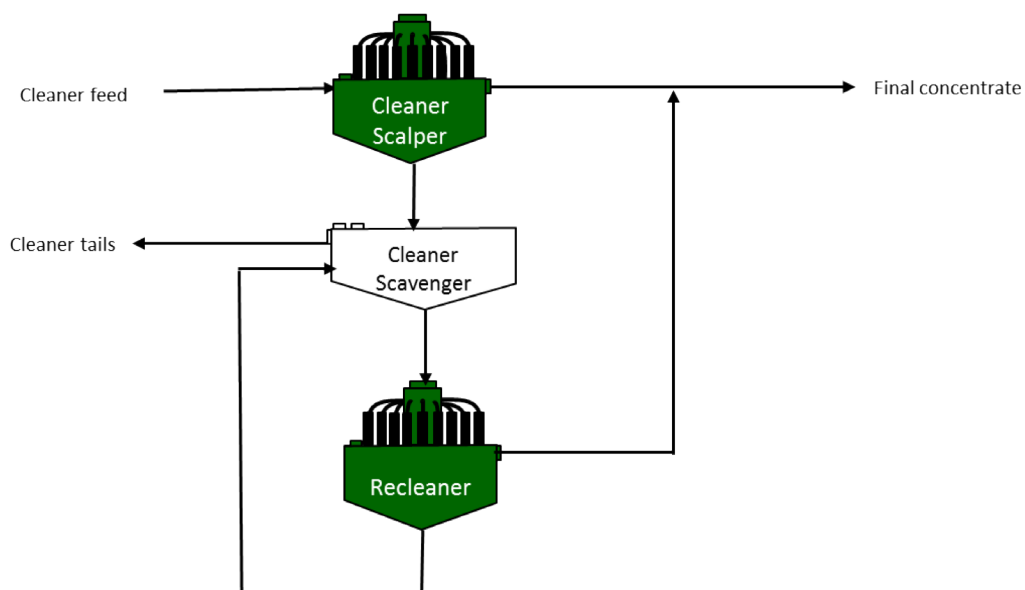

FIG 5 – Proposed new cleaner circuit design with Jameson Cell in cleaner scalper and recleaner duties.

This circuit achieves the grade benefits of fully froth washed concentrate with the long flotation times needed for ultimate recovery, in an overall smaller circuit than either technology could achieve alone.

In comparison to multistage mechanical cleaning circuits, this new circuit can replace two to three stages of traditional mechanical cell cleaning circuits. If further cleaning is required in the case of ultra-fine regrind circuits, the concept can be extended to include an additional third stage Jameson Cell, or an additional mechanical stage between the cleaner scavengers and the recleaner Jameson cell. If only two stages of mechanical cell cleaning are required, it may be possible to dispense with the second Jameson Cell and instead have the cleaner scavenger concentrate report to the cleaner scalper Jameson Cell. If regrinding is required in the circuit, the cleaner scalper cell could either be installed before or after the regrind mill. The optimum location is case-specific and depends on the liberation characteristics of the rougher/scavenger concentrate. The correct water addition for froth washing is determined once the mass flows around the circuit have been estimated.

The overarching principle of the proposed new circuit is to ensure that froth washed flotation machines produce the entire concentrate reporting to final product. The use of a scalper cell minimises the impact of feed variation on circuit performance and mechanical cleaner scavenger cells ensure a high overall cleaner circuit recovery. The circuit should be able to achieve a high enough and dynamically stable cleaner circuit recovery to allow the open-circuit disposal of cleaner tailings. Recently, CSA Mine has refurbished its old concentrator. The old two stage mechanical cell circuit was replaced with the new circuit as described here. The performance of the new circuit is presented as a case study later in this paper.

Choice of flotation technology

Although this paper describes the use of the Jameson Cell technology, the improved cleaner circuit design principles can be applied to other flotation machines incorporating froth washing, such as column cells. Column technology was invented in the 1960s but did not gain wide acceptance in base metals operations until the early 1980s. It is still a popular technology in the cleaning circuits of many operations in the Americas. Schena and Casali (1994) reported the use of this technology in various cleaner circuit configurations at different South American copper operations. However, column cells have not featured strongly in Australian operations. A review of these installations is provided by Lane and Dunne (1987).

The Jameson Cell has often erroneously been classified as a column cell probably due more to the similarity of applications rather than the separation technology. However, it operates on completely different principles and a more accurate description for the Jameson Cell is a reactor/separator type of flotation technology as stated by Finch (1995). Table 1 provides a comparison of the main characteristics of column and Jameson Cell technologies. Technology selection will always be a topic of debate and will be affected by individual experience. Ultimately, the best indicator of the strength of a flotation technology is the analysis of its performance in operating plants. This will account not for the 'design' or laboratory performance, but the actual performance over time in real plant conditions. This will include the ease of operation and maintenance, and the consistency of critical performance variables such as bubble size. Feedback from users and rigorous analysis of actual operating performance should prevail over laboratory or pilot results or 'head-to-head' testing. This is only meaningful if each technology can be accurately scaled up and can maintain the small-scale

TABLE 1

Characteristics of Jameson Cell and column flotation technology.

Column cell	Jameson cell
• Spargers (jetting or shearing types) required for bubble generation • Compressors required	• Air for flotation entrained from atmosphere • No compressors or blowers required
• Long residence time • Need large tank volumes	• Very short residence time • Small tank volumes (approximately five times less than 'equivalent' column cell) • Collection/contact in downcomer, tank used for separation only
• Low intensity – need large collection/contact zone (typically >15 minutes) • Disadvantage for fine particle recovery (Finch, 1998)	• High intensity for efficient bubble-particle contact (five to ten seconds in downcomer) • Total residence in tank (for separation only) is two to three minutes • Advantage for fine particle recovery
• Low/medium gas hold-up – ten to 20 per cent (Hernandez, Gomez and Finch, 2003)	• Very high gas hold-up (in collection zone) – 40 to 60 per cent (Jameson, 1988)
• Bubble size is typically 1500 to 3000 microns – jetting and shearing spargers (Pyecha *et al*, 2006; Lizama, Carrion and Estrella, 2008)	• Bubble size – typically 300 to 700 microns (Evans, Atkinson and Jameson, 1995) • Fine bubbles increase kinetics of *all* particles, not just fine ones • Fine bubbles mean higher carrying capacity and hence, productivity (production tonnage per square metre cell area)
• Need scale-up factor to account for short-circuiting (bypass) and differences in froth recovery/froth drop-back between pilot and full-scale cells (Dobby, 2002)	• Direct scale-up. Hydrodynamic conditions (jet velocity and mixing intensity) are the same between pilot plant and full-scale cells (Young, Barns and Pease, 2006) • No chance of short circuiting (so no bypass) – all feed has to pass through the downcomer at least once
• Medium/high maintenance – spargers and compressors • Sparger replacement typically six to 18 months	• Low maintenance – centrifugal fixed speed pump • Slurry lens orifice (to create high-pressure jet) replacement typically every +5 years
• Power required for compressors and recirculation pumps (Microcels and Cavitation tube-type columns only) • A portion of *tailings* is recirculated through cell, equal to many multiple times the feed flow	• Power required for downcomer *feed* pump • Tailings exit cell, a portion (less than or equal to feed) is mixed with fresh feed and passed through the downcomer again (giving another chance for particles to be collected) • Tailings are not simply recirculated through cell

performance (eg bubble size, operability) over the long run in a real plant.

Both columns and Jameson Cells use froth washing to control entrainment. However to achieve the higher grade in a smaller circuit needs fast flotation rates. In this respect column technology has a disadvantage because of its low flotation rates for fine particles due to the low mixing intensity (Finch, 1988; Dobby, 2002). In contrast, high flotation rates are a distinguishing feature of Jameson Cells, since they consistently provide very small bubble size and highly intense mixing. This is particularly important for the cleaning of finer streams, which are becoming more prevalent. This results in fast flotation rates necessary for the smaller more efficient circuits described here as ores become more complex and need finer regrinding for mineral liberation.

CSA Mine case study

CSA Mine is a copper operation 14 km north of Cobar in New South Wales, owned by Cobar Management Proprietary Limited (CMPL), a wholly owned subsidiary of Glencore. Its processing plant treats mainly chalcopyrite ore from its underground mine. Feed to flotation has a head grade around five per cent Cu varying from three to eight per cent Cu. The old flotation circuit consisted of roughing, scavenging and two stages of mechanical cell cleaning to produce final grade concentrate of 27.5 per cent Cu at over 96 per cent recovery. The large variations in the copper head grade often overloaded the circuits so operators had to use bypass plates in the launders of the first cells of both the roughers and the first cleaner bank to divert some concentrate directly to the final concentrate. The flotation circuit required considerable operator intervention and 'bypassing' material to final concentrate was never a preferred solution as it reduced the final concentrate grade.

In 2011, a project was initiated to increase throughput from 160 t/h to 205 t/h. This project was to be implemented over several years and included major changes to the grinding circuit as well as a complete overhaul of the flotation circuit which then consisted entirely of Denver cells installed in 1965 (Erepan, Rajiwate and Beehan, 2014). There was an initiative to increase concentrate grade and to reduce concentrate rail transport costs to the port of Newcastle. CSA Mine management requested a new cleaner circuit to increase concentrate grade to 30 per cent Cu without sacrificing plant recovery. The cleaner circuit now consists of an E4232/10 model (10 downcomer) Jameson Cell for cleaner scalping, three new Outotec TK40 tank cells for cleaner scavenging, and an E1732/4 model (4 downcomer) Jameson Cell for recleaning the conventional cell concentrate. The CSA flow sheet with the new cleaner circuit is shown in Figure 6. This cleaner circuit upgrade project was managed in-house by CMPL and was completed in October 2013.

Figure 7 shows the performance of the two Jameson Cells from surveys conducted during commissioning. The grade/recovery (Figure 7a) and selectivity curves (Figure 7b) for the two Jameson Cells, although quite different are in-line with expectations: the cleaner scalper cell produces a higher grade concentrate than the recleaner cell. The recovery in the cleaner scalper was quite high owing to the very large quantity of fast floating copper mineral particles in the rougher concentrate stream. The recleaner appears to be recovering a lot more composite particles as evidenced by the different copper selectivity response with silica compared to the cleaner scalper cell. The wide variation in data points is due to deliberately operating the Jameson Cells with different parameters (air flow rate, froth depth and wash water) to vary performance demonstrating that the Jameson Cells can be 'tuned' to operate at any point on the grade/recovery curve.

During the Jameson Cell surveys cleaner scavenger tailings were also collected to allow calculation of recovery across the entire cleaner circuit. Eight surveys over two days showed the overall cleaner circuit recovery to be over 98 per cent while producing a final plant concentrate grade averaging 29.5 per cent Cu. The overall plant recovery was maintained above the target of 96 per cent. Commissioning of Jameson Cells and the new cleaner circuit took place at a plant throughput of 160 t/h, and not the design criteria of 205 t/h for sizing the Jameson Cells as the plant is yet to ramp up to the higher tonnage. At the time of writing, the CSA Mine had been operating the new cleaner circuit for around five months. Figure 8 shows the plant concentrate grade approximately two years prior to the installation and since the new circuit was installed. In the months after the new circuit was installed, the plant treated more challenging ore, which has unusually
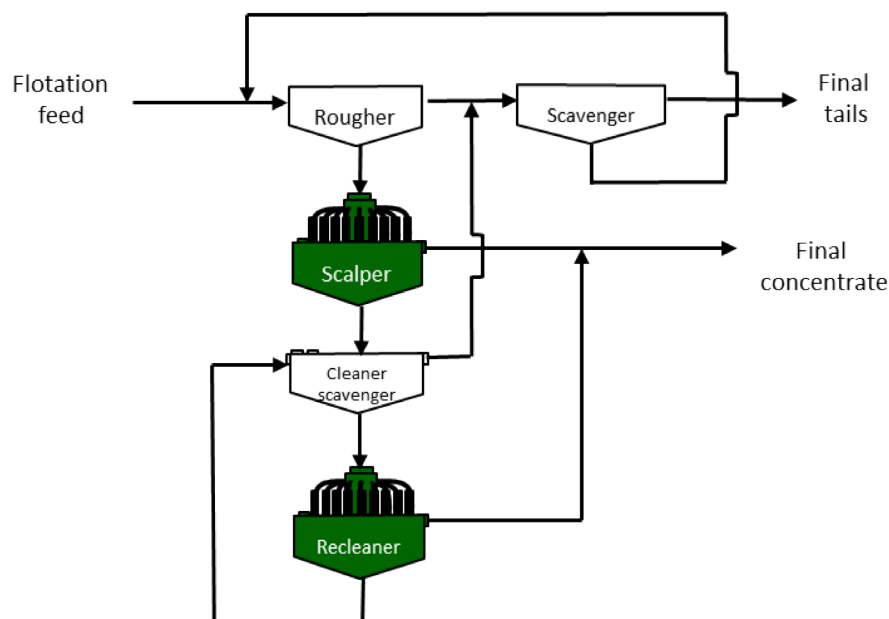

FIG 6 – Flow sheet at CSA Mine concentrator with new cleaner circuit with Jameson Cells in scalper and recleaner duties.
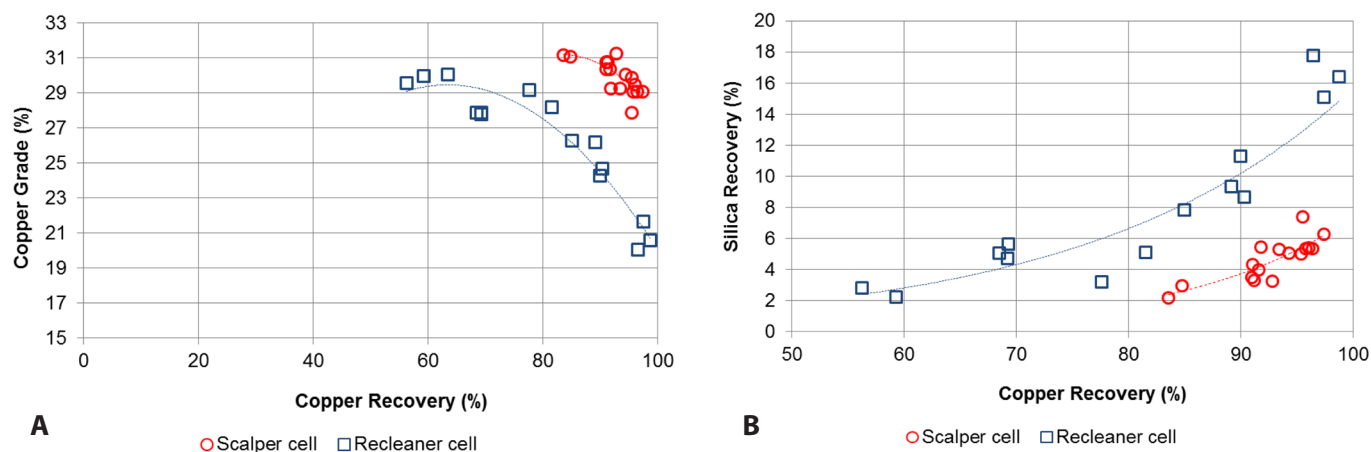
FIG 7 – (A) Copper grade/recovery and (B) copper/silica selectivity curves for the Jameson Cells at CSA Mine.
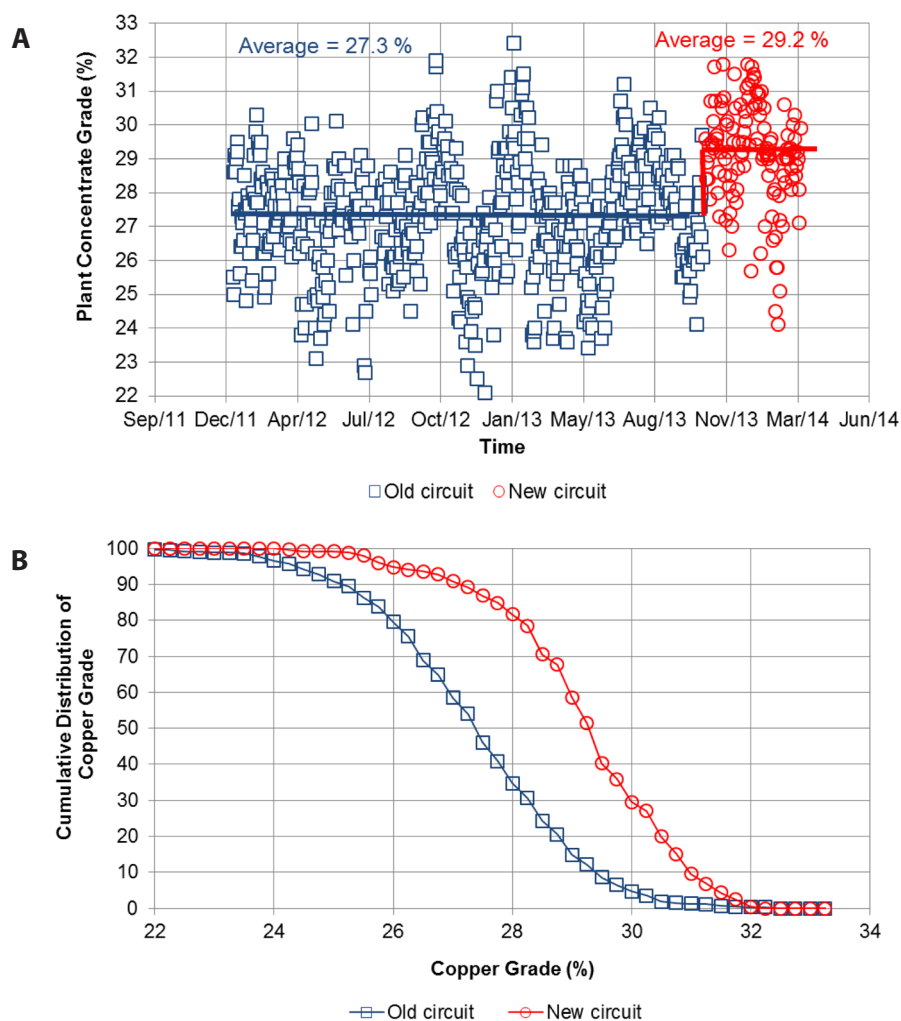

FIG 8 – CSA Mine final concentrate grade before and after installation of new cleaning circuit. (A) Plant final concentrate grade as timeline and (B) same data shown as cumulative distribution.

high quantities of readily floating pyrrhotite gangue and cubanite ($CuFe_2S_3$, 23.4 per cent Cu), which both tend to lower the final concentrate grade. However, the shift assays have showed that the new circuit is still capable of producing a higher average grade final concentrate (29.2 per cent Cu) compared with the old circuit (averaging 27.3 per cent Cu). The difference in final concentrate grade of the two circuits is more evident when the same data is plotted as a cumulative distribution curve as shown in Figure 8b. The ongoing aim is

to elevate the final concentrate to at least 30 per cent Cu which is expected to happen when the plant returns to treating the 'normal' ore type.

As well as higher concentrate grade, the plant reports significant operational improvements. The new cleaner circuit has proven to be much more robust and better able to handle the fluctuations in feed grade without operator intervention or the need to bypass material. The new operating strategy for the CSA Mine concentrator is to operate the cleaner scalper

Jameson Cell on the 'flat' part of the grade/recovery shown in Figure 6a and then 'tune' the recleaner Jameson Cell to achieve the overall desired cleaner circuit performance. For example, for maximum plant final concentrate grade, the recleaner should be operated below 80 per cent unit recovery as silica recovery increases significantly above this point as shown in Figure 6b. However, if a circulating load builds up around the cleaner circuit and starts to affect (decrease) overall plant recovery, the recleaner Jameson Cell can be 'pulled' harder to reduce the load to the cleaner scavenger bank. The short residence time of the new circuit ensures it responds quickly to such changes.

Interestingly, another copper operation in Australia has been operating Jameson Cells in the new cleaner circuit configuration since 1995, although that was not the initial intent. Jameson Cells were originally designed to operate in a two-stage cleaning configuration, but during commissioning it was quickly realised that the first cleaning stage was already producing final grade concentrate, making a second stage of cleaning redundant. As a result these cells were altered to treat the concentrate from the conventional cleaner scavenger bank instead. So in fact the improved cleaner circuit is not even new. The only difference is that the Jameson Cells installed at CSA Mine are much more 'user friendly' being the latest Mark IV design compared with those at this copper operation which are the much earlier Mark II design.

Other proposed benefits

So far discussions on the new cleaner circuit design have focused purely on the benefits in metallurgical performance. To explore other potential benefits for greenfield projects, the new cleaner circuit design was compared to commonly designed 'standard' flow sheet. The size and number of mechanical (or column) cells required for the standard cleaner circuit was selected by an independent engineering design house while design of the new circuit was undertaken by the authors. It is assumed the three concentrators are treating copper ore (chalcopyrite as the economic mineral) with head grades between 0.5 to 1.0 per cent Cu. The three projects are described as follows:

- Project A is a small/medium sized plant (<1000 t/h) where the cleaner circuit has three stages of conventional cleaning, designed in the usual counter-current closed circuit configuration
- Project B is a medium/large sized plant (>1000 and <3000 t/h) where the cleaner circuit has three stages of conventional cleaning, again designed in the usual counter-current closed circuit configuration
- Project C is a very large copper plant (>5000 t/h similar to those typically seen in porphyry copper operations) where there are also two stages of cleaning, but mechanical cells are only used for the first cleaner stage whilst column cells are chosen for recleaning.

Table 2 compares the most important design aspects of the two cleaner circuit designs:

- number of cells installed – less cells means lower installation costs, less ongoing operating, maintenance and spare parts costs
- circuit total residence time – shorter residence time makes for a more robust and responsive circuit that is faster to 'tune' and optimise
- footprint – smaller footprint has obvious advantages in foundation and structures, building and installation costs
- installed motor power – for consideration of ongoing energy usage and cost.

Table 3 compares these parameters for the two different circuit designs. It shows significant benefits in the new cleaner circuit, mainly as a result of the reduction in number of cells and total cell volumes. In summary, it shows that for the three scenarios, the improved circuit design reduces residence time by around 70 per cent, footprint by 30–50 per cent and uses 30–40 per cent less power. This design comparison is a simple exercise that can be independently estimated by potential users for their application.

The development of a lower cost circuit that is also more effective is a significant step. As is often the case, the 'step change' is not really new; rather it has been 'assembled' by combining existing knowledge and developments. It has been developed in brownfields applications with specific constraints and objectives. This provided a low risk demonstration and development of the concepts, equipment and techniques. Several other brownfield projects are now following this success and implementing circuits to produce all final concentrate from Jameson Cells. In the common pattern, successful application at brownfield sites leads to adoption for greenfield projects. At the time of writing several projects at definitive feasibility stage (DFS) have the new cleaner circuit locked into the flow sheet design.

Laboratory tests to simulate 'new' cleaner circuit design

Flow sheet development occurs early in the metallurgical development of an orebody and is typically conducted on a small number of blended drill core intervals to represent the ore. At this stage, required reagent schemes, pulp chemistry

TABLE 3

Potential savings of the new cleaner circuit design over standard designs.

Project	Circuit residence time (%)	Footprint (%)	Installed motor power (%)
A	71	54	37
B	73	33	30
C	74	43	30

TABLE 2

Comparison of standard and new cleaner circuit designs.

Project	Standard circuit design				New cleaner circuit design			
	Number of cells	Residence time (minutes)	Footprint (m²)	Installed motor power (kW)	Number of cells	Residence time (minutes)	Footprint (m²)	Installed motor power (kW)
A	15	319	88	385	7	92	41	243
B	19	210	188	1413	7	58	126	995
C	22	245	732	5498	12	64	417	3839

conditions, grind size targets and overall circuit configuration are developed by conducting a series of 'standard' tests. The overall flow sheet is settled before applying the same set of conditions over a much greater range of ore-variability samples to develop flow sheet design criteria and metallurgical models for economic evaluation. Flow sheet development test work is conducted in laboratory batch experiments, with locked cycle tests generally being conducted on a select number of samples to confirm closed-circuit performance and flow rates for design purposes. Depending on the complexity of the orebody and the owner's risk appetite, a continuous pilot plant evaluation of a large bulk sample may be carried out, or mini-continuous pilot plant runs may be completed on multiple samples.

To evaluate the improved cleaner circuit for a new orebody, a practical and accurate laboratory evaluation procedure is needed during this stage of design. Such a procedure, using standard laboratory equipment, has been developed and is described here.

The Jameson Cell scales up very accurately from continuous laboratory and pilot scale rigs. However this requires volumes that can be impractical for laboratory testing. Fortunately, a procedure to accurately simulate Jameson Cell performance using standard laboratory batch cells has been developed and verified. Several of the brownfields applications described in this paper successfully used this approach. For example, Seaman *et al* (2012) described laboratory tests used to justify installation of two Jameson Cells at Telfer without the need for pilot plant testing. The full-scale performance of these cells was predicted by dilution batch tests. This procedure can be applied with reasonable confidence for the new cleaner circuit design when developing a flow sheet for a greenfield project.

Figure 9 compares dilute batch flotation test selectivity of copper versus penalty element recovery with parallel pilot Jameson Cell performance over a wide range of operating conditions. In each case, the batch dilute flotation test was carried out by collecting a sample from the operating plant, then diluting the slurry in process water to ensure the slurry solids content was less than ten per cent w/w. Following this a batch flotation test was conducted with frother as the only reagent added (and only as required) to ensure generation of a stable froth during the test. Unlike conventional batch tests, these dilution tests were conducted with very low scraping (froth removal) rates, eg ten to 20 second intervals (with froth paddles slowly pulled across the froth) to allow as much drainage from the froth as possible.
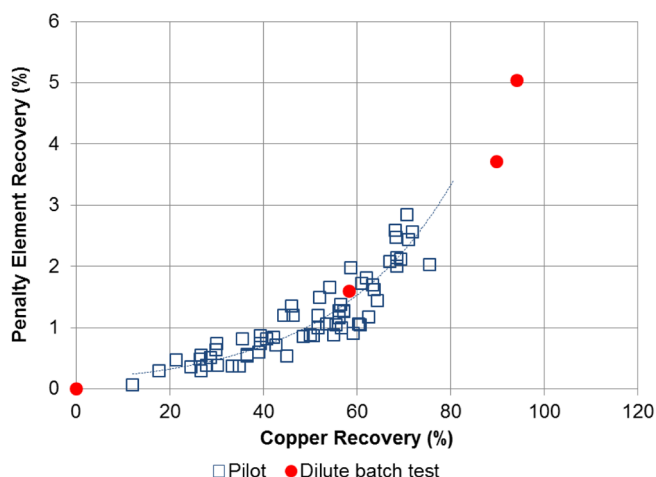

FIG 9 – Pilot Jameson Cell versus dilute batch flotation test selectivity.

Figure 10 shows an example of a complete testing regime that can be conducted for a new project to simulate the new cleaner circuit design. The recommended procedure is as follows:

- After regrinding (if required), place slurry (rougher concentrate) in a laboratory batch flotation cell and dilute to less than 10 wt per cent solids.
- Condition with relevant collectors, depressants, pH modifiers.
- Add frother throughout the test as required to maintain a stable froth phase and maintain the level of the cell with addition of water to give approximately 15–30 mm froth depth. Adjust airflow so that the froth is almost free-flowing over the launder.
- Collect concentrates by using a very slow scraping rate of the entire froth phase into a container. Suggested scrape rates are once every 20 seconds, with the paddle pulled very slowly (taking approximately 15 seconds for one scrape) across the froth in order to maximise concentration of valuables and to minimise entrainment of gangue.

The above procedure is applied to simulate both Jameson Cell stages (cleaner scalper and recleaner). To test the cleaner flow sheet shown in Figure 10b, a suitable flotation time or concentrate mass pull for the cleaner scalper must first be identified. This involves conducting a test where four to five concentrates are recovered from the rougher concentrate (Figure 10a) and analysing the resulting selectivity curve of the
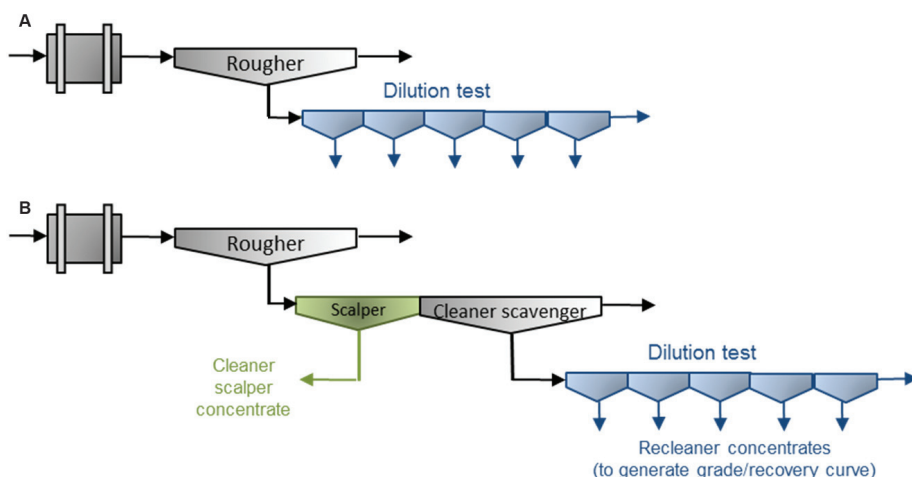

FIG 10 – Laboratory flotation test procedure to simulate the new cleaner circuit design. (A) Cleaner scalper batch test, (B) complete cleaner circuit batch tests.

cleaner scalper. The optimum point would be located left of the 'knee' of the selectivity curve. For example, in Figure 9 this would target copper recovery of approximately 50 per cent. In this case, the concentrate was collected only after one minute (three scrapes). If flow sheet development time or ore sample quantity is limited, an arbitrary time of one minute (or three scrapes) should be used as standard — experience has shown that this is close enough to the targeted recovery/grade for a copper circuit for a cleaner scalper duty.

The cleaner scavenger stage batch flotation test is carried out as a regular batch test following the removal of the cleaner scalper concentrate using the normal ten second scraping rates to remove the remainder of the floatable mineral particles. Then, a final dilution cleaner test will need to be conducted on the cleaner scavenger concentrate using a similar flotation time as that used to generate the rougher concentrate, with multiple concentrates collected in order to generate a grade/recovery curve to represent the entire cleaning circuit. The procedure described above for the new cleaner circuit design and shown in Figure 10b is also suitable for locked cycle tests as per typical practice for any other cleaner circuit design.

The actual residence times in the cleaner scalper and recleaner stage are not relevant for scale-up determination as residence time plays no role in the sizing of Jameson Cells. This information is only required for the sizing of the cleaner scavenger bank. The results from these tests should then allow the design engineers to use the grade and recovery numbers generated for equipment selection. The sizing of the Jameson Cell for each duty is provided by the flotation technology vendor. Rather than looking at each duty in isolation, the criteria for the design of the entire cleaner circuit is:

- to ensure there is sufficient capacity in the Jameson Cells to produce the desired range of plant final concentrate tonnages
- to ensure that there is sufficient capacity in the cleaner scavenger bank to allow the tailings from these cells to be sent to final tailings.

CONCLUSIONS

Case studies have been presented showing that the introduction of Jameson Cells into cleaning circuits has enhanced selectivity by increasing fine gangue rejection whilst maintaining or improving overall cleaner circuit recovery. A new cleaner circuit design has been presented, along with operating data from CSA Mine where the circuit was implemented as part of an expansion to the operating plant. The circuit design promises not only improved metallurgical performance, but also greater stability in the face of feed variation, a more robust operation and is more operator-friendly with a lower maintenance requirement.

The improved cleaner circuit design is relatively new for greenfield projects, although it has been already well proven in several brownfield cases. A laboratory procedure for development of this new circuit has been presented using dilution batch tests which have been proven to scale-up to both Jameson Cell pilot plant and full-scale plant data. This allows accurate prediction of the performance of this circuit in routine laboratory flow sheet development. This new approach will position the industry to process the more challenging ore types that are expected in the future where the emphasis will be on consistent operation and achieving high recoveries at target grades from poorer quality ores. The relatively small number of current installations has already demonstrated the potential for both new and existing plants and the opportunities will continue to emerge.

As well as the significant improvement in concentrate grade/recovery performance, the new cleaner circuit significantly reduces the required number of cells and equipment compared to current standard cleaning circuit designs. This means that better performance can be achieved in less space, for lower capital cost, lower operating cost, and significantly less energy use.

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