Enhancing the Performance of Cu-Mo Circuits Using the Jameson Cell

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ABSTRACT

It has been argued that, molybdenite particles, due to their shape, may be more sensitive to hydrodynamic effects than copper mineral particles. The platelet shaped molybdenite particles may align along streamlines and thus have lower probability of collision with bubbles. Increasing turbulence would increase collision frequency and efficiency, and therefore increase the rate of particle collection.

In a Jameson Cell the high shear generated by the plunging jet, breaks the entrained air into a multitude of very fine bubbles and provides increased bubble/particle collisions. The hydrodynamic conditions for particle collection inside the downcomer and separation in the tank are identical between laboratory, pilot plant and full scale Jameson Cells. Scale up is direct and proven. This high intensity can provide the best conditions for improving the flotation of molybdenite in bulk copper/molybdenite flotation.

Case study examples of pilot scale demonstration of improved molybdenite flotation in copper/molybdenite flotation will be discussed.

INTRODUCTION

Flotation has been described by Araya et al (2013) as a complex multifaceted process and as a flotation triangle of ore, chemistry and machine characteristics. Each plant and mineral system will have more or less influence by each of these factors. When separating floatable mineral from non-floatable minerals the use of machines with froth washing is important to minimise entrainment. When recovering floatable valuable minerals such as chalcopyrite/molybdenite or floatable minerals where only one is valuable such as chalcopyrite/pyrite, separation may rely on the ore and the design of the process to treat it, chemistry and in particular machine features.

The most important factor affecting flotation devices is their ability to make small bubbles as this dictates both the flotation kinetics and the carrying capacity. Ensuring effective bubble particle collisions and maximising froth recovery will ensure high recoveries and effective use of installed capacity. The Jameson Cell provides an excellent device to achieve moderate recovery at high carrying capacity and excellent separation from non-floatable gangue. Its use where valuable minerals are to be floated such as in the bulk flotation of copper minerals and molybdenite takes advantage of its excellent collection efficiency and froth stability. The inclusion of wash water maximises concentrate grade by eliminating entrained gangue minerals. Examples of the excellent performance of the Jameson Cell for copper-molybdenum flotation and the supporting reasons are outlined with examples from laboratory and pilot plant operations and the application of these results to plant scale Jameson Cells.

THE JAMESON CELL

The Jameson Cell technology was invented in the late 1980s to overcome the design and operating deficiencies of column and conventional flotation cells. From its first commercial installation in 1989 it has been continuously improved to make it more robust and easy to use. Over 340 have been installed throughout the world in various flotation duties. The latest cells combine the original advantages of small bubble size and small footprint with new low maintenance and operator-friendly designs. The Jameson Cell is a flotation device driven by fluid mechanics. The advantages of this innovative machine are:

- Consistent fine bubble generation with no external equipment or spargers.
- Intense mixing with small bubbles achieving rapid flotation without mechanical agitation.
- High throughput in a small footprint.
- Froth washing maximizes concentrate grade in a single flotation stage.
- Fast response and easy control.
- Steady operation and performance irrespective of changes in feed flow.
- No moving parts, simple to install and maintain, excellent availability.

With conventional or column flotation technologies scale up factors are required when using laboratory or pilot plant results for full scale design. These factors account for variations in cell geometry, mixing patterns (short circuiting) and energy intensity between the different sized units. Scale up factors may also change depending upon the duty, feed characteristics and flotation kinetics.

For Jameson Cell design no scale up factors are required. This is because the jet velocity, air entrainment and hydrodynamic conditions for mixing are identical across different sized cells from laboratory to full scale. The operating principle and process parameters of the downcomer are exactly the same irrespective of cell size. For large cell sizes simply more downcomers are used. Direct scale up has been proven across different applications including coal, base and precious metals, solvent extraction and industrial minerals. Two examples of the scale up from pilot plant to full scale for base metals are given in Figure 1.

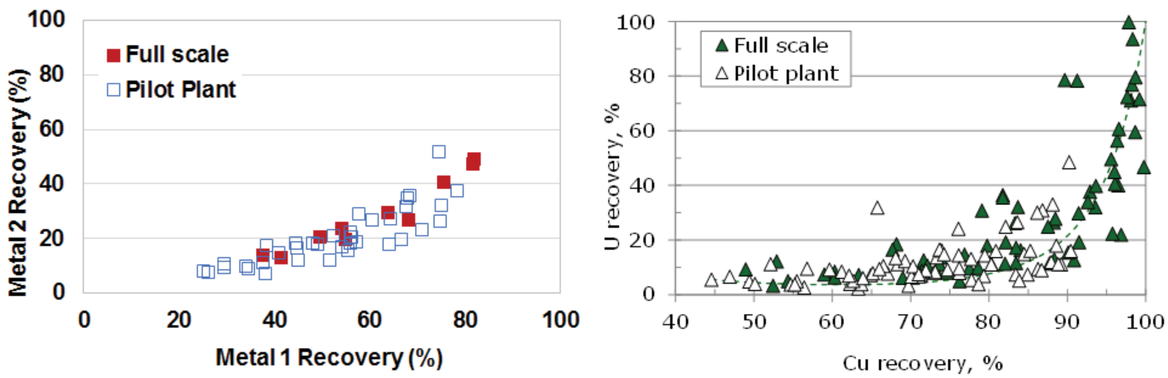

Figure 1 Examples of pilot plant and full scale demonstrating scale up

Continuous onsite pilot plant testing can provide risk mitigation for projects and provide the metallurgical data required to justify the capital cost of mineral processing circuit modification. It is not however necessary as the Jameson Cell can be also scaled up from laboratory scale work. The laboratory work can be in a pilot L150 Jameson Cell or by performing dilution cleaning tests onsite, as designed by Glencore Technology. These tests have been described by Huynh et al (2014) and were effective as justification for several Jameson Cell installations to date. An example of the lab dilution testing and pilot scale results is shown in Figure 2. These laboratory tests can be conducted by plant operators and over time can demonstrate feed variability to better predict expected improvements through entrainment elimination on different plant streams. Wash water addition in pilot and full scale Jameson Cells is fundamental to the rejection of entrained gangue.

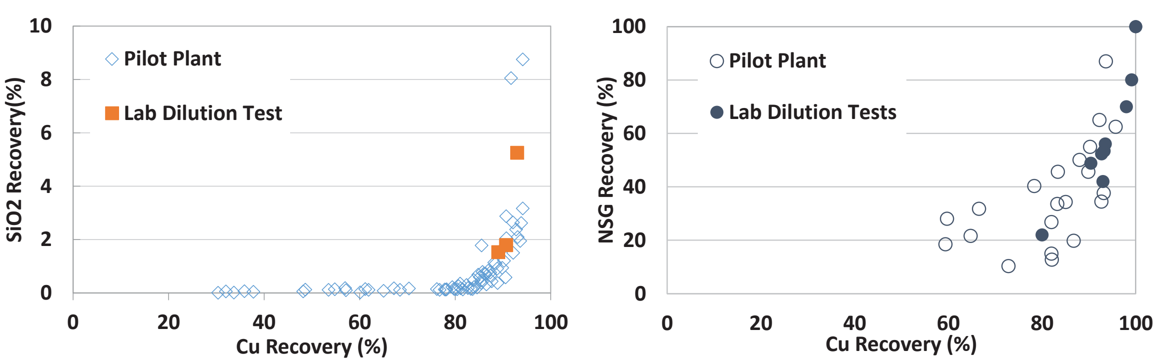

Figure 2 Comparison of pilot plant results and laboratory dilution flotation tests

Collision Efficiency

The flotation process comprises the collision between air bubbles and mineral particles with mineral particles adhering or attaching to the air bubbles and subsequently being transported to the froth phase. This whole process is called collection and the efficiency of collection, E, may be expressed as:

$$E = Ec.Ea.Es \qquad (1)$$

where E_c is the collision efficiency, E_a is the attachment or adhesion efficiency and E_s is the stability efficiency. In the Jameson Cell there is a high mixing velocity and a large interfacial area and thus there is rapid contact and capture of the hydrophobic particles by the bubbles. In effect, with high voidage fraction, pulp is a thin film surrounding air bubbles. This mechanism where the flotation tank acts as a disengagement vessel where froth is discharged from the bottom of the downcomer into a quiescent environment enables high stability efficiency.

Particle recovery by flotation is sensitive to both particle size and contact angle (Crawford and Ralston, 1988). The traditional recovery by size curve demonstrates that fine particles (<10 μm) and coarse particles (> 100 μm) float poorly. The reason for the poor flotation of these particles differ; fine particles are more likely to follow streamlines in a flotation cell and thus collision efficiency is reduced, while coarse particles are more likely to be detached from bubbles due to the turbulent or disruptive forces in the flotation cell. Improved flotation should be seen when both turbulence increases bubble particle collection and a quiescent zone is provided to decrease particle detachment and the froth recovery is maximised. The Jameson Cell provides this environment.

Carrying Capacity

Finch and Dobby (1990) described a model developed by Espinosa-Gomez et al (1988) to represent the carrying capacity in flotation; which has been widely used across flotation technologies and applications. The model was based on the particle size d_p and the particle density ρ_p.

$$C_a = K d_p \, \rho_p \qquad (2)$$

Pilot and full scale testwork determined a linear relationship for fine particles in pilot and small industrial columns. Further work by Patwardhan and Honaker (2000) refined the model using data from numerous laboratory, pilot and full scale operations of the Jameson Cell. The new model was determined as;

$$C_a = k d_{50}^{a} \sigma^{d} \frac{n_p d_{50}^{3} \rho_p}{d_b^{3}} J_g \qquad (3)$$

In which

$$n_p = \frac{2 d_b}{d_b - \sqrt{(d_b^2 - d_{50}^2)}} \qquad (4)$$

and

$$d_b = b_c J_g^{c} \qquad (5)$$

where d_{50} is the mean particle size, σ is the size distribution modulus, a, b, c, d, and k are constants, d_b is the bubble diameter and J_g the superficial gas velocity in cm/s. b_c is a constant with three different values for laboratory, pilot and full scale columns; due to observed decreases in carrying capacity due to increases in column cross sectional area and were determined experimentally. For additional information on the key parameters refer Patwardhan and Honaker (2000).

Jameson Cells are renowned for high carrying capacities and have been reported to be higher than columns and conventional flotation cells. Based on the model above the reason is due to the small bubble size, high contact efficiency and high froth recoveries due to a quiescent zone for froth recovery and small tank volumes and residence time. From equation (3) bubble size is a key determinant of carrying capacity that distinguishes Jameson Cells. Evidence of small bubbles are given in the work of McGill University and are shown in Figure 3.

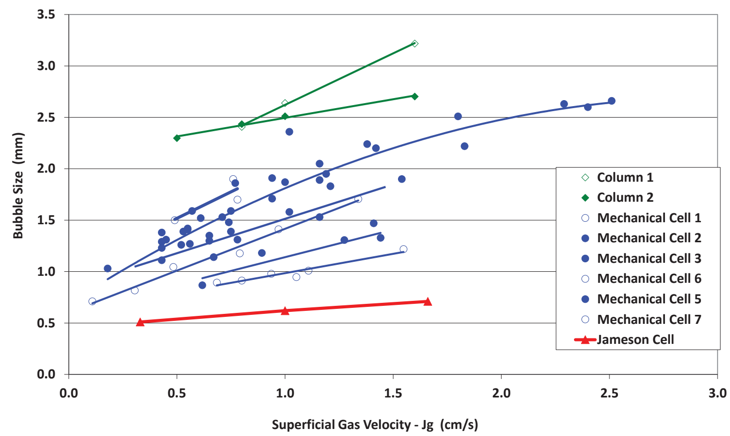

Figure 3 Bubble size as a function of Jg for different flotation technologies

An example of demonstrated carrying capacity improvements can be seen in the example given in copper flotation where the pilot Jameson Cell was operated on the column feed and achieved significantly improved carrying capacities compared to the operating columns. Improvements up to a factor of three were seen and are shown in Figure 4.

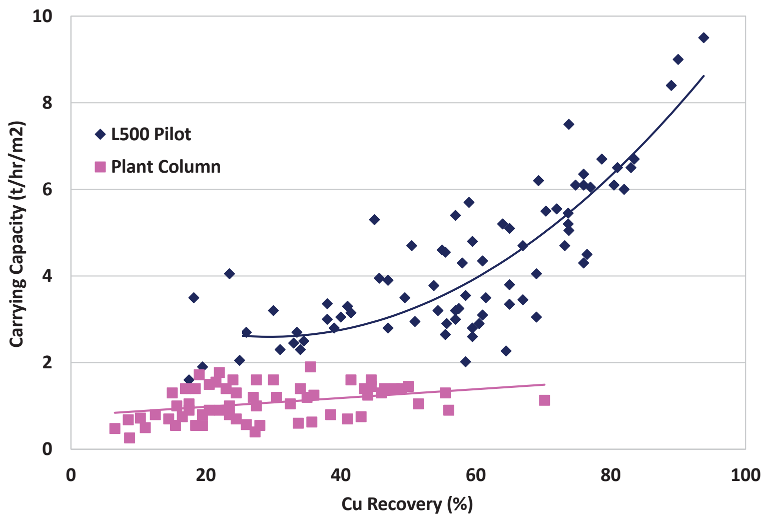

Figure 4 Carrying capacity for a pilot Jameson Cell compared to the operating column

Froth Recovery

Zanin, Grano and Ametov (2010) performed surveys around a copper/molybdenum cleaning column to determine the relative contributions of the collection zone and the froth phase. To do this they collected metallurgical samples from different points including a sample just below the pulp/froth interface and performed size-by-size analysis. The copper behaviour was typical of that seen in copper columns with the intermediate 30 micron particles having higher recovery than the finer and coarser particles. The molybdenum recovery was very low with less than 10 per cent across all size ranges. Their analysis determined that molybdenum grade was depleted across the froth phase while copper was enriched. This led the authors to conclude that the froth recovery of molybdenum is much lower across the column than the copper recovery.

Seaman, Franzidis and Manlapig (2004) suggested that the selective rejection of particles in the froth may be the result of one of the following three mechanisms;

1. Detachment of less strongly attached particles as the aggregates arrive at the pulp/froth interface. This would be caused by forces exerted on the aggregate as it rapidly changes momentum on hitting the interface.
2. Selective detachment of particles from bubble surfaces during coalescence events occurring within the froth and bubbles bursting on the froth surface. This is unlikely to occur, it is expected that this process is non-selective due to the sudden rupture of bubble lamellae.
3. Selective reattachment of particles that drop off bubbles during coalescence. This process is not likely to occur in a highly loaded froth due to a lack of available sites for reattachment.

Seaman, Franzidis and Manlapig (2006) propose that the froth recovery of attached particles in a flotation cell is selective based on particle size, density and hydrophobicity. They showed the selective transfer of attached particles across the froth phase. The pulp/froth interface was responsible for a large degree of upgrading of the particles attached to bubble surfaces and also a significant proportion of the recovery loss across the froth phase. Honaker and Ozsever (2003) studied the detachment process for systems where the conditions converged from kinetic limiting conditions to carrying capacity limiting conditions under conditions where entrainment was largely eliminated. They noted a significant enrichment across the froth zone under high solids loading conditions and concluded that the detachment process is selective, with particles having the weakest bond with the bubble surface are preferentially detached.

Further work by Honaker, Ozsever and Parekh (2006) established that conditions where carrying capacity limitations applied, resulted in improved flotation selectivity due to the selective detachment as a result of bubble surface reduction and the reflux process that occurs between the collection and froth zones. Plant based measurements of Rahman, Ata and Jameson (2015) using the device described in Rahman, Ata and Jameson (2013) investigated the effect of plant variables on the froth recovery. Not unexpectedly the air rate was found to have a significant positive effect on the recovery of particles; in both the collection and the froth zones, although the decrease in concentrate grade resulted as lower grade particles were recovered. The froth depth was also found to have a significant effect where froth recovery decreased significantly as drop back increased resulting in significant upgrading of particles. The plant results indicated a froth recovery in the order of 75 to 85 per cent could be achieved with an appropriate choice of operating parameters as might be seen in a continuous concentrator. As Jameson Cells operate at shallower froth depths than columns this may contribute to improved froth recovery.

When trying to selectively sulphide minerals large circulating loads can be used to increase the competition for bubble space to remove the less hydrophobic particles as circuits are operated close to carrying capacity limitations. This has been reported in the separation of copper from nickel and in the flotation of pentlandite from pyrrhotite (Lawson et al 2014). This same effect in copper/molybdenum flotation is unintentional and undesired. Welsby (2014) determined that molybdenum required greater froth stability to reach maximum recovery, likely due to competition in the froth between highly hydrophobic copper minerals and moderately hydrophobic molybdenite for the limited bubble surface area. Operating at levels of four to seven times the critical coalescence concentration for the frother was required for molybdenum; whereas two to three was adequate for copper. This would infer that the positive results seen in Jameson Cells may include the contribution of improved froth stability.

The Flotation of Molybdenite

Molybdenite consists of a molybdenum atom surrounded by six sulphur atoms arranged as a hexagonal layer structure. Although there is also a trigonal system it is less common (Castro et al, 2016). Within the layers the S-Mo-S are strong covalent bonds while weak Van der Waals forces exist between the adjacent S-S sheets. As suggested by Triffett et al (2008) these weakly bonded layers are easily pulled apart in grinding circuits. This structure and the resultant product of the comminution circuit results in particles that may have strongly hydrophobic faces and inert edges. It is these factors that are likely to be the main drivers of individual particle hydrophobicity. Molybdenite is characterised as a hydrophobic anisotropic mineral (Laskowski, 2012). This group also includes talc and graphite.

Ametov et al (2008) argued that this shape factor associated with molybdenite particles could be the reason for the lower flotation recoveries in flotation circuits compared to the performance of copper minerals in the same circuit. In their supporting work the use of increased turbulence was used by decreasing the solids density in the pulp in both laboratory and plant circuits was intended to demonstrate the increased turbulence at lower solids density would have a positive impact on the bubble particle collision efficiency. The results of their work showed that although copper recovery was unaffected by changes in flotation feed density molybdenite recovery was affected and resulted in increased recoveries at lower flotation feed densities. This effect was demonstrated in both the operating plant through surveys and in laboratory tests of the flotation feed. Copper and molybdenite grades were improved at the lower feed density.

The suggestion from the work by Ametov et al (2008) is that both particle morphology as well as cell hydrodynamics may be important in the recovery of molybdenite. The molybdenite particles due to their shape are more likely to align along streamlines which would reduce their likelihood of colliding with bubbles. The improvement in recovery from their work was from a significant improvement from the coarser particles. This improvement in the coarse particles was also hypothesized to be because of the high face-to-edge ratio compared to fine particles that have a higher edge contribution to their surface behaviour.

Other work conducted in operating copper/molybdenite plants includes that by Hernandez-Aguilar and Basi (2009) at Highland Valley Copper mine. This study focussed on the molybdenum circuit and in particular the final two columns of the cleaning circuit. A decreased bubble size resulted in a 4-5 fold increase in production rate production rate and recovery of the columns and a minor increase in grade when a large proportion of bubbles less than 1mm in size were generated.

In addition to differences in flotation performance as a result of changing hydrodynamic conditions Triffett and Bradshaw (2008) identified correlations between ore types that likely resulted in a decreased molybdenite recovery when the ore types were blended. This decrease in performance was more significant for molybdenite than copper minerals. Subsequent laboratory testing of these hypotheses by Zanin et al (2009) confirmed that molybdenite is more sensitive to the operating environment than copper sulphide minerals. Higher concentrations of Ca, Mg, Fe and K were measured on the slow floating molybdenite which correlated to the presence of skarn ores.

Molybdenum flotation is affected by ore type as well as by its anisotropic nature. The flotation conditions that were suggested in plant trials to improve its flotation can be correlated to similar improvements in its flotation in Jameson Cells. Although hydrodynamic factors are significant there will likely be occasion when ore type drives performance.

CURRENT PLANT CIRCUITS

Flotation circuits in both North and South America are generally designed to include a circulating load across the column cleaner stage to enable high circuit recovery in spite of the generally low molybdenum stage recovery in columns. This design feature has been reported by Zanin, Grano and Ametov (2010) and Bulatovic, Wyslouzil & Kant (1998). Zanin, Grano and Ametov (2010) discussed the performance of a typical copper/molybdenum flowsheet using conventional flotation cells and flotation columns. In the example given the unit recovery across the cleaner column was 56 per cent for copper and only 7 per cent recovery of molybdenum. The overall plant recovery of 67 per cent was only achieved by a very high circulating load returning molybdenite to the column feed. Through measurements of the solids located just below the pulp/froth interface Zanin, Grano and Ametov (2010) concluded that the copper was enriched across the froth phase while the molybdenum is depleted.

Some plant data are provided to demonstrate this behaviour in Table 1 where four sites operating primary columns have copper recoveries of 55 to 65 per cent with molybdenum recoveries of 7 to 23 per cent. The cleaner scavenger circuits recover in excess of 95 per cent of the remaining copper and molybdenum to generate high circulating loads to enable satisfactory overall circuit recoveries.

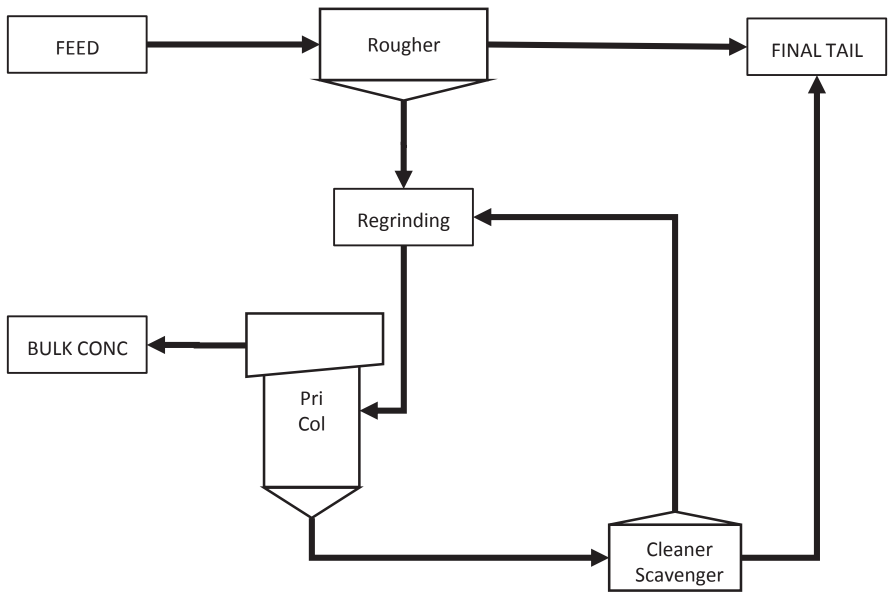

Figure 5 Typical bulk copper molybdenum flowsheet

Table 1 Plant stage recoveries

	Cu Recovery	Mo Recovery	Cu Upgrade	Mo Upgrade	Cu:Mo Selectivity
Site 1					
Primary Col	59	17	1.4	0.4	3.5
Scavenger Col	84	76	1.3	1.3	1.1
Site 2					
Cleaner	67	33	7.8	3.8	2.0
Cleaner Scavenger	94	92	1.1	2.8	1.0
Site 3					
Primary Col	65	15	3.9	0.9	4.3
Cleaner Scavenger	98	92	2.0	2.0	1.1
Site 4*					
Primary Col	56	7	2.3	0.3	8.0
Cleaner Scavenger	99	99	NA	NA	1.0
Site 5					
Primary Col	55	23	NA	NA	2.4

* from Zanin, Grano and Ametov (2010)

JAMESON CELLS FOR PRIMARY CLEANING

From the discussion provided on molybdenum flotation and from the provided plant data provided in Table 1, it can be seen that the recovery of molybdenum is low across the columns and cleaner cells likely due to poor bubble size distribution, low collection efficiency, poor froth recovery and potentially carrying capacity limitations. Given that these specific conditions are all better in a Jameson Cell an improvement in performance would be expected.

Figure 6 compares laboratory and pilot L500 Jameson Cell results for four different operations. As previously demonstrated the laboratory and pilot results agree indicating that laboratory data is sufficient for demonstrating expected Jameson Cell performance. In two operations the existing column circuits are also surveyed and a comparison is provided. In all cases the Cu:Mo selectivity is improved in the Jameson Cell and high copper and molybdenum recoveries were possible at all sites. The performance of each of the sites are slightly different and factors such as liberation, chemistry and ore types are likely contributing factors.

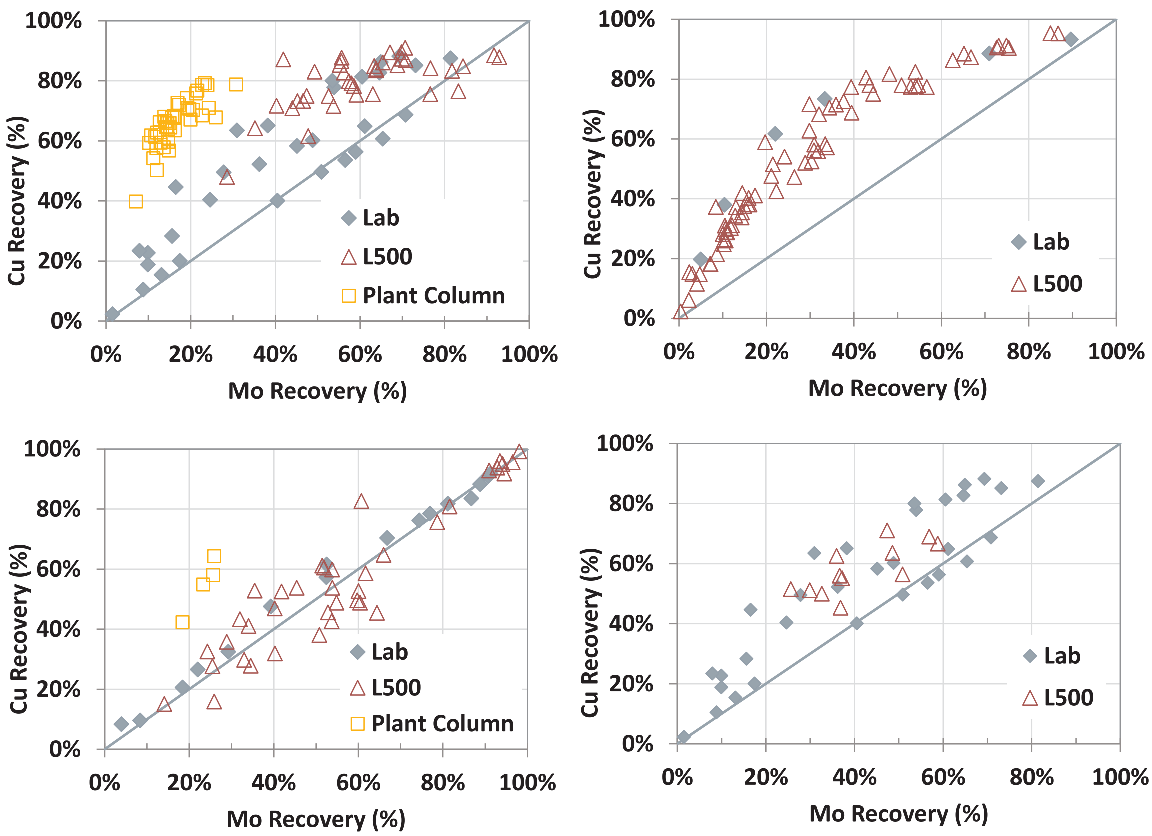

Figure 6 Jameson Cell performance for copper molybdenum primary cleaner

CONCLUSIONS

Evidence from testing at operating plants shows Jameson Cells are able to be scaled up directly from laboratory to full scale. This is because the jet velocity, air entrainment and hydrodynamic conditions for mixing are identical across different sized cells from the laboratory L150 cell to full scale. In addition to the L150, traditional laboratory tests have been developed that simulate their performance and can be done easily on site to determine the benefits of a Jameson Cell over a wide range of plant operating conditions. Examples of scale up from laboratory L150 cell and from dilution cleaning tests to L500 pilot tests and to full scale operation have been demonstrated.

The flotation of molybdenum in copper molybdenum circuits has often been seen in plant practice to suffer low recovery in the primary cleaning circuit. To ensure acceptable plant recoveries a bank of conventional cells is generally used as a cleaner scavenger to recover the molybdenum and generate a high circulating loads back to the cleaner. The poor recovery of molybdenum compared to copper can be the result of low collision efficiency, poor froth recovery and selective drop back from the froth phase and possibly as the carrying capacity is exceeded. The use of a Jameson Cell in this duty has several hydrodynamic advantages that have been demonstrated in pilot plant trials. The smaller bubbles, intensive mixing and shallow froth depths enabling high froth recovery, enable in some cases 1:1 copper to molybdenum recovery.

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