Benchmarking Performance of the Two-Stage StackCell™ with Conventional Flotation for Copper Sulfide Applications

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ABSTRACT

Rougher flotation in sulfide ore applications is typically performed using conventional flotation machines. The trend over the last 100 years has been for these cells to become larger in volume with cells reaching sizes of 600 m^3 and in some cases even larger. The associated foundation loadings, transport and installation requirements along with building size have also increased. In an economic environment where projects must be executed with dwindling capital supply, bigger is not always better. More recently, industry is being challenged to identify new technology that allows for improved flowsheets and financial returns through efficiency gains. To meet this challenge, a novel high-intensity two-stage flotation system known as the StackCell™ was tested to potentially achieve installation volume and required retention time gains when compared to conventional flotation circuits. The results from on-site pilot scale work conducted on typical copper concentrator rougher flotation feed showed retention time gains on the order of 6 to 9 times when compared with conventional flotation equipment. This finding has the potential of reducing capital demands for rougher flotation circuit designs when incorporating the StackCell. The results from test work will be discussed in this paper showing comparative test data generated with a Denver bench batch test, pilot StackCell and large conventional cells, all receiving the same feed.

KEYWORDS

Flotation, Two-stage Flotation, Flotation kinetics, Scale-up

INTRODUCTION

Over the last few years, a number of flotation devices have been described as two-stage or multi-stage flotation units. The idea behind multi-stage flotation devices is that flotation performance can be improved by utilizing cells with multiple specialized units in series, but not all units of the same type, as is practiced in trains of multiple tank cells or columns. Instead, each unit is specially designed to provide the optimized fluid environment for each stage of the sequential flotation process. This idea has been proposed based on a study of the fundamentals of the flotation process, and the realization that the process consists of discrete sequential processes, that are each optimized with dissimilar process conditions (Finch et al, 1995), (Zhou, 1996). Instead of executing each step simultaneously in a homogeneous fluid environment, where the conditions would be a compromise between particle collection and froth recovery, the multi-stage flotation unit operates in a set of segregated process environments, each with a set of conditions optimized for that step.

Examples of two such multi-stage reactors are the Staged Flotation Reactor (SFR) by Woodgrove and the StackCell by Eriez. In the case of the StackCell, there are two units in series; the first promotes highly turbulent mixing of air and feed slurry to optimize bubble-particle collection, and the second promotes quiescent fluid conditions to promote bubble-particle buoyancy with minimized drop-back.

There are two important questions that are raised in the introduction of new technology that are germane for acceptance and commercialization. The first is the question of how these new units can be scaled up. In the case of columns and tank cells, there are well established methods for estimating the scale-up from laboratory-scale tests to full production mass flowrates. The second question is how does the metallurgical performance of a 2-stage unit like the StackCell compare against the incumbent technology, large mechanical cells. The purpose of this investigation is to answer both of these questions, using a case-study developed at a concentrator processing feed from a large copper porphyry ore body.

BACKGROUND

Lower ore grades and a desire to simplify mineral processing flowsheets have started a trend to increase the size of flotation units (Mankosa, 2017). This trend has focused on processing larger quantities of ore, rather than improving the efficiency of the unit operation. Figure 1 shows the classic “elephant curve” for a number of porphyry copper ores (Bulatovic, 2007). This curve shows empirically that the recovery in classical mechanical tank flotation exhibits a kind of pass-band behavior with respect to particle size. Flotation is effective in the middle decade, but decays quickly for large particles and finer particles. Another way to see this is to look at the metal deportment by size in the tailings of a conventional concentrator. When this is done, it will be apparent that most of the lost recovery is represented in the fine and coarse fractions.

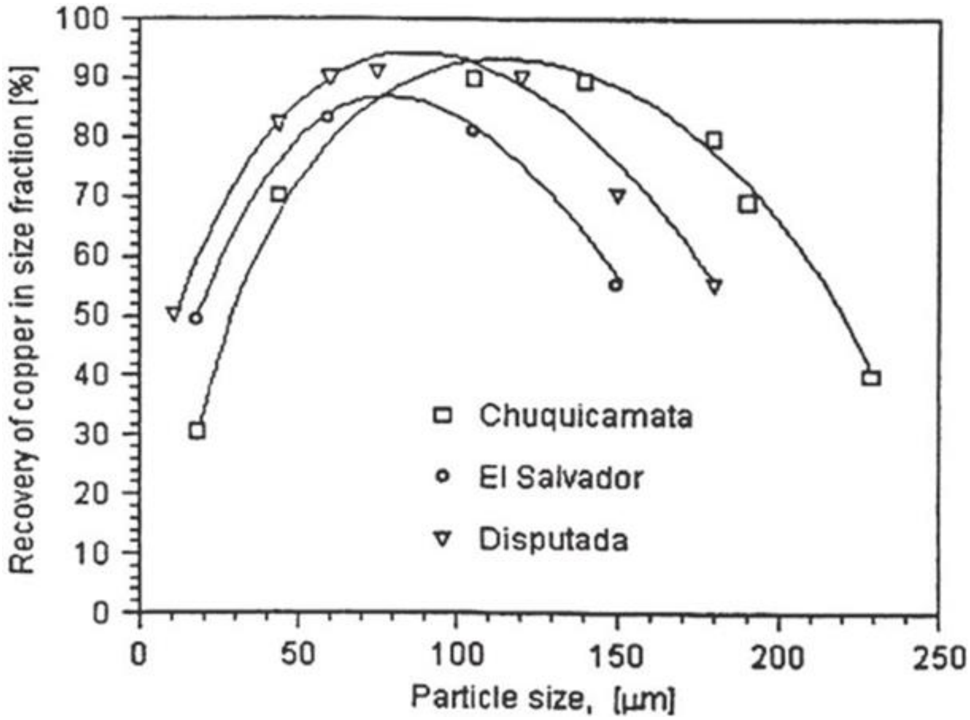


Figure 1: Recovery by size for various copper concentrator operations.

To understand the limitation of flotation performance exemplified in Figure 1, many researchers have studied the flotation process. It has been recognized that the overall process is a combination of kinetics and mass transfer. Equation 1, written in the notation of chemical kinetics for discussion purposes only, shows the overall process.

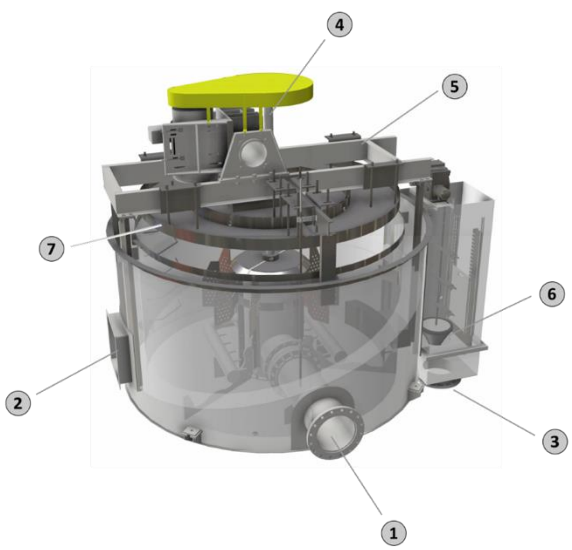
$$\text{Bubble + Particle} \underset{\text{detachment}}{\overset{\text{attachment}}{\rightleftarrows}} \text{Bubble-particle aggregate} \xrightarrow{\text{transport to launder}} \text{Recovered particle} \qquad (1)$$

The rate of the first step is often represented as being of first order, driven by collisions, and therefore proportional to the product of the concentrations of bubbles and particles. The rate constant, especially for fine particles, is often represented as being activated by the extent of local fluid turbulence (Williams, 1983), which reflects the observation that the efficiency of collisions is increased by their energy. This is related to the low inertia of fine particles. The first reaction is also represented as being reversible, meaning that the bubble-particle aggregate, which is capable of floating out of the pulp, is not a final product, but actually a very fragile intermediate one. It is possible for these intermediate products to break apart by the phenomenon of "drop-back", as the result of acceleration from local turbulence in the pulp, deceleration at the pulp froth interface or coalescence of bubbles in the froth phase (Falutsu, 1989). The second reaction shown in Equation 1, which is actually better described as being a mass transfer process, occurs as buoyant forces lift the bubble-particle aggregate out of the pulp, driven by the difference between the apparent density of the bubble-particle aggregate and the host fluid. This process will predominate over the reverse reaction in a low energy fluid environment.

Equation 1 and Figure 1 provide an explanation of why fine particle recovery is poor in conventional mechanical cells and why it becomes worse as the particle size distribution becomes finer. For mechanical cells, the intensity of mechanical energy introduced through the shaft is used to prevent sanding of coarse particles, control bubble size, create turbulence for collisions, and create forced convection for transport of bubble particle aggregates out of the collection zone. The first three of these are all favoured by increasing energy density, while the fourth will cause "drop-back" as the energy is increased. Therefore, a mechanical cell operates with an amount of energy that is a compromise which allows most of the particles to be collected, while accepting losses on the coarse side because of "drop-back" and on the fine side because of insufficient energy for particle collection.

One solution to solve this problem and maximize particle recovery is to use two stages, which are hydraulically isolated, and which allow high specific energy in the first unit to maximize collection, followed by low specific energy in the second tank to maximize froth recovery. The StackCell was designed with this philosophy. Figure 2 shows a cut-away of the StackCell. In this configuration, the StackCell consists of two tanks, one inside the other. The internal tank, called a "sparging unit", consists of a rotor-stator configuration, which receives the feed slurry and air from the bottom of the unit. The feed travels from the bottom to the top, with a residence time distribution that is designed to approximate a plug-flow. The internal tank is hydraulically isolated from the main tank on all sides except through a gap between the side walls and a baffle or lid on the top of the vessel. This ensures that the residence time is controlled in the internal tank. It also operates at a slightly higher pressure than the main tank, which provides a gradient preventing slurry from returning from the external tank to the internal tank. This is all done to create ideal conditions for bubble-particle collection in the internal tank. The second tank is operated without any mechanical agitation, and acts purely to separate the bubble-particle aggregates into a froth phase, which is recovered in a launder.

StackCells have been used for coal cleaning since 2007 and units up to 3 metres in diameter are in service. They have also attracted attention in gold and base metals, for example in zinc and copper/molybdenum flotation and also in flotation systems with slow-floating fines, that normally require prohibitive residence times.



1. Inlet
2. Outlet
3. Tails Feed Discharge
4. Rotor
5. Main Supporting Structure
6. Dart Valve
7. Wash Water Pan

Figure 2. A StackCell cut-away, showing the inlet (1) to the sparging unit or internal tank, concentrate outlet (2), tails outlet (3).

Two important questions arise when evaluating the suitability of the StackCell for flotation trains, especially rougher/scavengers. Firstly, what is the best approach for scaling up the flotation dynamics of the StackCell so that lab-scale results can be used to estimate the performance of large units? Secondly, how do the flotation dynamics compare against conventional cells, in other words, is there actually an improvement in performance with the 2-stage approach.

For conventional mechanical cells, scale-up is often estimated based on the results of a bench-scale Denver-cell laboratory batch test. In this test, the cumulative recovery and grade are plotted versus time to generate a flotation response curve. To estimate the predicted response of large cells, the cumulative time axis is traditionally multiplied by 2-2.5 to account for the increase in transport distances, short-circuiting and other inefficiencies that occur in larger industrial-scale mechanical cells. Then the residence time (RT) is transformed to cumulative reactor volume (V) using the anticipated volumetric flow-rate F, as shown in Equation 2.

$$V\,[\mathrm{m}^3] = (2.0 - 2.5)\ \mathrm{X}\ \left[\mathrm{RT}\,[\mathrm{h}]\ \mathrm{x}\ \mathrm{F}\ \left[\frac{\mathrm{m}^3}{\mathrm{h}}\right]\right] \tag{2}$$

The number and size of cells, as well as launder design etc. are selected from the recovery and grade curves generated from the Denver batch test. Although it has been pointed out that froth scraping, rotor speed and other variables are not always consistent between tests, this simple scale-up method has proven very robust, and remains a credible method for estimating the size and number of large flotation trains. It has the advantage that the Denver test is easy to perform, the apparatus is readily available, and the methodology is time-tested. In fact, pilot plants for rougher flotation are not generally deemed necessary unless there is some concern about issues such as the effect of recycle streams. This study was carried out to show that StackCell performance in trains could also be estimated based on the Denver lab test.

EXPERIMENTAL

In this study, a train of three 0.61 metre diameter StackCells were run in a large copper/molybdenum plant. A photograph is shown as Figure 3. They were run side-by-side with conventional mechanical roughers and scavengers during normal operation with standard conditioning. In this plant, each rougher/scavenger row consisted of two roughers and three scavengers. Concentrate from the two roughers are combined, and the concentrate from the three scavengers are combined separately. Therefore, the roughers and scavengers were each treated as a separate block for the purposes of generating two mass balances. The inlet and outlets of each block (rougher and scavenger) were sampled during each StackCell test run. As shown in Figure 4, a small representative slip-stream was sampled from the production streams and sent to a ¼ inch (6.4 mm) diamond mesh/expanded metal sieve bend, followed by a holding tank. The sieve bend was added as a trash screen, and the tank was provided to ensure steady flowrate to the StackCell train.

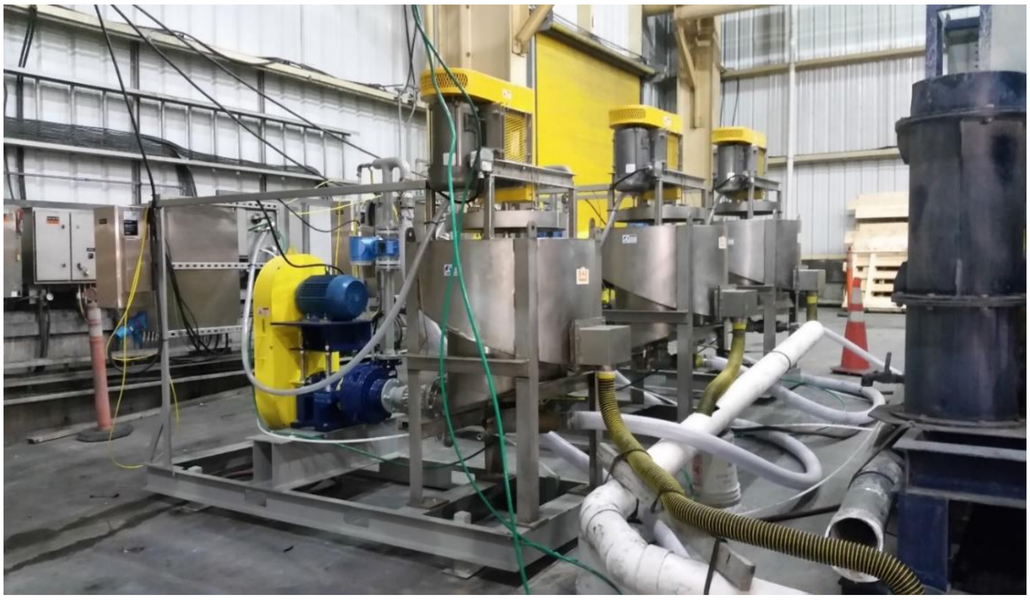


Figure 3: The train of three 0.61 metre diameter StackCells used in this pilot study.

The set-up allowed the StackCell train to be fed from the feed of the production roughers, or the tails of the production roughers, which was the feed of the production scavengers. Sampling was done around each individual StackCell (sample points are denoted by "S" in Figure 4). For all sampling, representative measurements were taken of copper, iron, molybdenum, water and solids, and volumetric flowrate. After any changes in process inputs around the StackCells, the system was left untouched for 15 minutes before taking a sample cut, and 15 additional minutes were allowed before the second and third cut. The residence time in each StackCell was less than 1 minute, in other words the time constant of the cells were much less than the time allowed for equilibration after a process change. The assayed sample was therefore a composite of three samples collected over 1 hour of presumed steady state. The production units were sampled over the same time period to allow for a "side by side" comparison of the StackCells and the conventional mechanical cells. For each set of runs, mass balances were closed around the production rougher bank block (consisting of two cells), the production scavenger bank block (consisting of three cells) and each StackCell. The mass balances were closed using a standard optimization algorithm to minimize the sum of squares of the residuals between experimental measurements, constrained by the equations of mass continuity. Finally, for each campaign (production rougher feed and production scavenger feed), representative samples were taken to a local independent commercial laboratory for standardized Denver bench scale tests. As a result, the flotation response versus time was obtained for commercial cells, pilot StackCells and the Denver batch test cell, all from the same feed.

The comparison of the conventional cells with the StackCell train was conducted over a number of days. We will be reporting here on the days when Denver tests were conducted on the same feed. For two of these days, the StackCells were run with production rougher feed ("rougher feed" stream in Figure 4) and on one day, with feed being directed from the production rougher tail ("scavenger feed" stream in Figure 4).

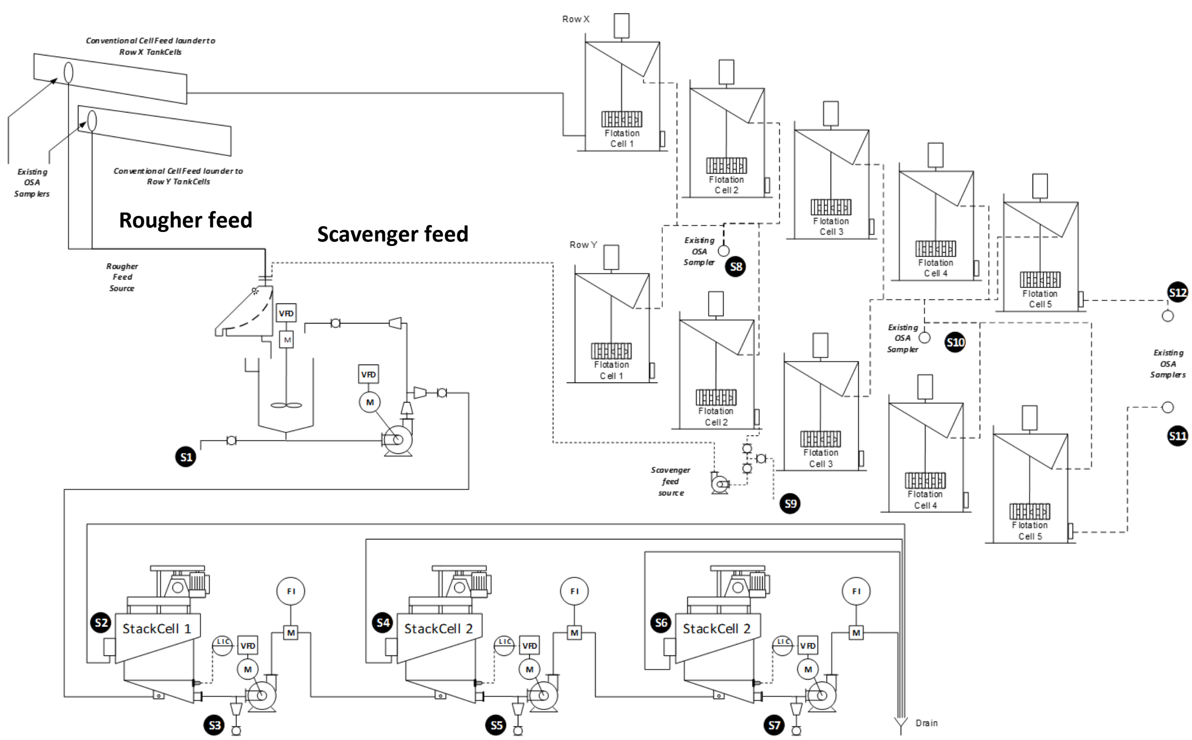


Figure 4: Block diagram showing the experimental configuration for these pilot plant campaigns.

RESULTS

Rougher feed sample

Samples were obtained for five sets of StackCell tests (annotated as A-E in Figure 5) on a day in which sampling was performed on the mechanical cell circuit. For this set of experiments, the StackCell train received feed from the same feed as the production roughers (shown as "Rougher feed" stream in Figure 4). These samples were measured, and the mass balances were reconciled as explained in the Experimental section. Also during this day, a representative time averaged sample was collected and taken to a commercial lab to measure the flotation response in an 8 litre Denver batch test on the same day (annotated as kinetics test A in Figure 5). No additional reagents except for frother were added, and the test was run at the same percent solids as the sample. The 80th percentile of the cumulative size distribution of that sample (p80) was 160 microns. A comparison of the kinetic responses for the production cells, the StackCell train and the Denver batch test are shown in Figure 5. In Figure 5A (left hand side), the kinetic response curves for five StackCell tests are shown, along with the corresponding curve for the Denver Lab test. The residence time considered for the StackCell was the combined residence time in the inner tank (sparging unit) and outer tank. In Figure 5B (right hand side), the corresponding points for the production rougher and scavenger banks are also included. Kinetic curves for the StackCell and the production mechanical cells are fitted to the experimental data points by multiplying the Denver batch curve result by 0.35 for the StackCells and by 2.0 for the production mechanical cells.

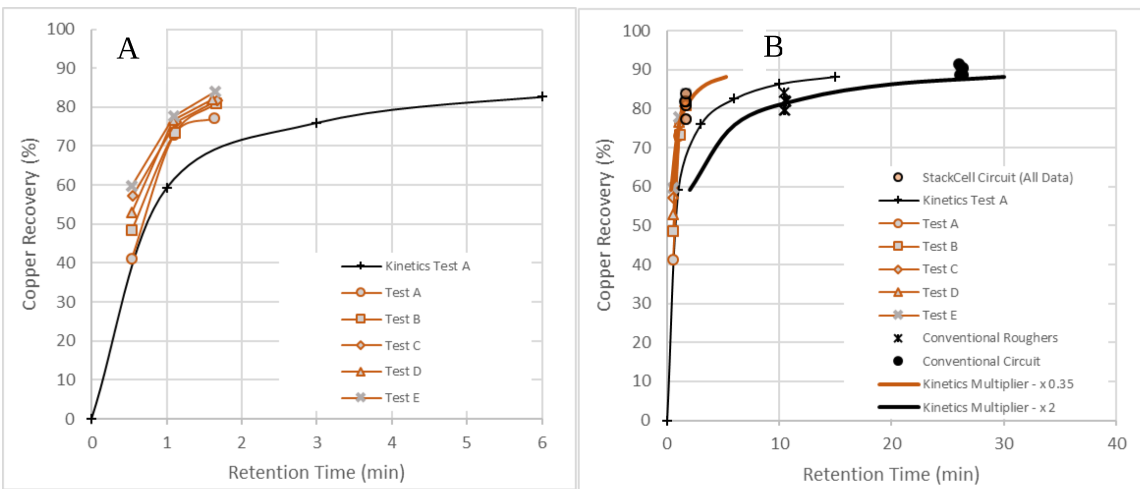


Figure 5. Rougher kinetic responses for five tests conducted on a StackCell train in parallel with production mechanical cells and a Denver batch test, all receiving the same feed.

This experimental scheme was repeated on another day, also using rougher feed for the StackCells. In this case, the size distribution of the feed sampled for the Denver test had a p80 of 250 microns. The flotation kinetic curves are shown below as Figure 6. In this case, the StackCell tests are annotated as F-J and the Denver lab batch test is annotated as kinetics test B.

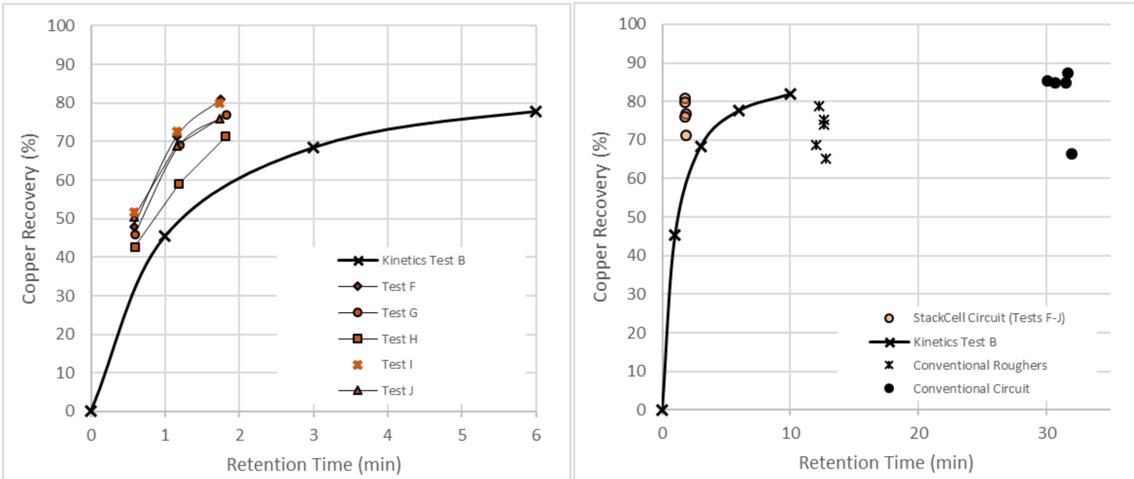


Figure 6. Rougher kinetic responses for five tests conducted on a StackCell train in parallel with production mechanical cells and a Denver batch test, all receiving the same feed.

The average cumulative grade and recovery results for the comparison of the StackCell, Denver batch test and production units, all being fed the same rougher feed, are shown in Table 1.

Table 1: Average flotation parameters for rougher feed benchmarking campaign (average of tests shown in Figure 5 and Figure 6)

Flotation type	Cumulative Recovery (%)	Combined Grade (%Cu)	Time (min)
StackCell	79.92	14.63	1.86
Production Rougher	78.31	15.51	11.79
Denver	80.17	17.56	6.0

Scavenger feed (rougher tails) sample

On the other day in which sampling was performed on the mechanical cell circuit and the Denver Lab batch cell, the StackCell train received feed from the same feed as the production scavengers (shown as "Scavenger feed" stream in Figure 4). During this day, six StackCell experiments were conducted, annotated as tests K-P. Samples were measured, and the mass balance for each experiment was reconciled as explained in the Experimental section above. The production units were sampled, and a representative sample was taken to a commercial lab to promptly measure the flotation performance in an 8 liter Denver Lab batch test on the same day, annotated as kinetics test C. A comparison of the kinetic responses for the production cells, the StackCell train and the Denver Lab batch test is shown in Figure 7 and Table 2.

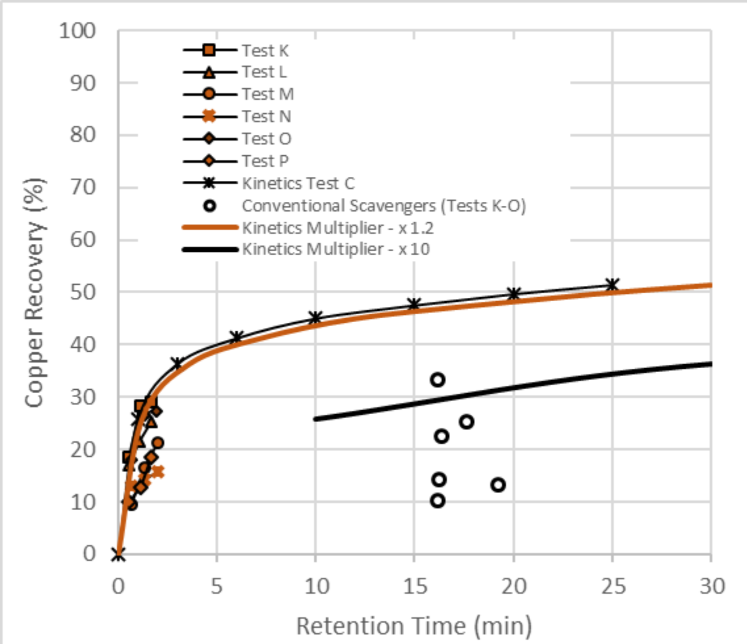


Figure 7. Kinetic responses for six tests conducted on a StackCell train in parallel with production mechanical cells sampled at the same time and a Denver batch test, all receiving the scavenger feed.

Table 2: Average flotation parameters for scavenger feed benchmarking campaign

Flotation type	Cumulative Stage Recovery (%)	Sc Grade (%Cu)	Time (min)
StackCell	24.79	3.59	1.72
Production Scavenger	27.03	3.02	16.97
Denver	36.37	2.58	3.0

DISCUSSION

In both Figure 5 and Figure 6, when we have benchmarked flotation performance using typical rougher feed, the kinetic response of a train of three StackCells is substantially accelerated in comparison with the results from the Denver batch test. The scaling factor for equal recovery from batch test duration to residence time in the continuous StackCell process is less than unity, with both test campaigns suggesting a scaling factor of about 0.40. With the same feed, the scaling factor from the Denver batch test to production mechanical cells retention time is about 2.0, which is in line with industrial experience. This suggests that the Denver tests results are reasonable and consistent in their expected relationship with the performance of the production cells.

Part of the reason for the accelerated kinetics of the StackCells could be their relatively small size in these tests (0.6 metres in diameter versus commercial cells which are multiple metres in diameter). Future work will evaluate whether this scaling factor is also valid for larger sized StackCells. However, the size factor cannot explain all of the difference, because the StackCells are actually much larger than the Denver cell, and they seem to be more than two times faster in performance. It would seem that the effect of segregating bubble-particle collection and froth recovery, as discussed in the Background section above, is contributing to the superior performance of the StackCell in this study.

When the StackCells are fed from the scavenger feed (Figure 7 and Table 2), both the StackCell train and the production mechanical cells seem to suffer in performance compared with the Denver result.

In this case, the scaling factor for the StackCells is now slightly higher than unity, while the performance of the production cells is 10 times slower than the Denver result. These results suggest that there were significant inefficiencies for conventional production cells in picking up slower floating species. This is also true for the StackCell, but not to the same extent. Because there were only three StackCells in series, it was not possible to determine whether additional cells in series would have allowed additional recovery, or whether the curve would have reached a plateau. Other work performed on tailing streams has indicated that 0.61 metre diameter StackCell trains are more than three times faster than Denver batch tests (Christodoulou, 2016).

SUMMARY AND CONCLUSIONS

These results suggest that a straightforward Denver batch test could be used as the basis for sizing trains of StackCells, as is done currently for mechanical cells. Compared with large mechanical cells, the StackCells have substantially faster kinetics. Some of this effect may be caused by the relative size of the StackCells that were tested. Future work will investigate how these scaling relationships can be extended to larger StackCells. However, these results, with StackCells in continuous operation show significantly improved flotation performance, even in comparison with a Denver cell. This suggests that two-stage flotation can offer significantly improved performance.

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