A HIGH RATE MECHANICAL FLOTATION CELL FOR BASE METAL APPLICATIONS

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ABSTRACT

Mechanical cells are the dominant unit operation in base metal rougher flotation applications worldwide. As economic demand for metals increase, and as the feasible ore grades decrease, the installed capacity of mechanical flotation units worldwide has greatly increased, adding significant capital and operating cost. One opportunity to improve this situation is to use fundamental knowledge to make the industrial flotation process more efficient. A key insight is that the flotation process can be optimized by dividing the processing of the pulp into two distinct fluidic environments; a collection cell where air and pulp mix in a highly energetic compartment , and a low energy gravity separation cell. This is the basis of the "2-stage flotation device" that has been patented by Eriez and marketed under the tradename StackCell™.

Two industrial case studies will be presented to highlight the potential metallurgical and commercial advantages of the StackCell. In the first, a train consisting of three pilot scale StackCells (each 0.6 metre diameter) was run in parallel with a train of conventional mechanical cells in a major copper concentrator and benchmarked against a batch Denver test. In the second, the performance of a 3 metre diameter StackCell in a nickel sulfide cleaning application was benchmarked against a batch Denver test. The flotation kinetics observed in the StackCells were 2.4 to 2.9 times faster when compared with the lab Denver test. In the first case study, the kinetics of the StackCell was about six times faster than conventional mechanical cells. It is hypothesized that the efficiency improvement in kinetics is because of reduced "drop-back" during the froth recovery phase, which is reduced because of the reduction in the shear that is present in a conventional mechanical tank cell.

This result suggests that a 2-stage flotation system can be used to reduce the working volume of flotation units by five to six times. This would allow operators to significantly reduce the size of their flotation lines for a comparable flotation objective. Some discussion will follow about the scale-up criteria, maintenance and operability issues, comparisons of layout, and possible cost savings.

INTRODUCTION

The solution that most equipment suppliers have offered to reduce the cost of mechanical flotation equipment over the last 30 years has been to increase the size of the flotation unit cell (Mankosa, 2017). For example, three 100 m^3 machines with three smaller motors, mechanisms and control valves could be replaced with a geometrically similar 300 m^3 with a larger version of each ancillary component. While there are some efficiencies and cost improvements to be gained by this approach, it does not take advantage of fundamental insights into the flotation process, and it does not represent a step-change in terms of process design or economic benefit for the customer. The advantage of the “bigger is better” approach is that there is past experience of incremental improvements by making cells larger and there is a well-established scale-up method, which allows practitioners to estimate equipment capital costs based on very simple laboratory test-work. A different paradigm, which is gaining interest rapidly is to use a unit operation in which it is easier to optimize the flotation process, which will be described in this paper. This approach is often referred to “2-stage flotation”. Because this approach is new, it is important to benchmark it against existing conventional technology and to demonstrate a robust methodology for sizing equipment and flowsheets. This paper aims to address these issues with two case studies.

Even world-class concentrators operated by some of the largest and most sophisticated miners in the world, have inherent inefficiencies using conventional technology. Evidence of this is shown as Figure 1, which shows two histograms showing metal content by size for the tailing streams for two large (ie. greater than 100,000 tonne per day) concentrators, one from North America and one from South America. Typically, 8-15% of copper identified as ore and fed into the process is lost by reporting to final tailings. About 85% of that is lost in the combined size classes that are below 50 microns or greater than 150 microns -which coincides with the range in which conventional flotation is not efficient. The reason for this inefficiency will now be explained.

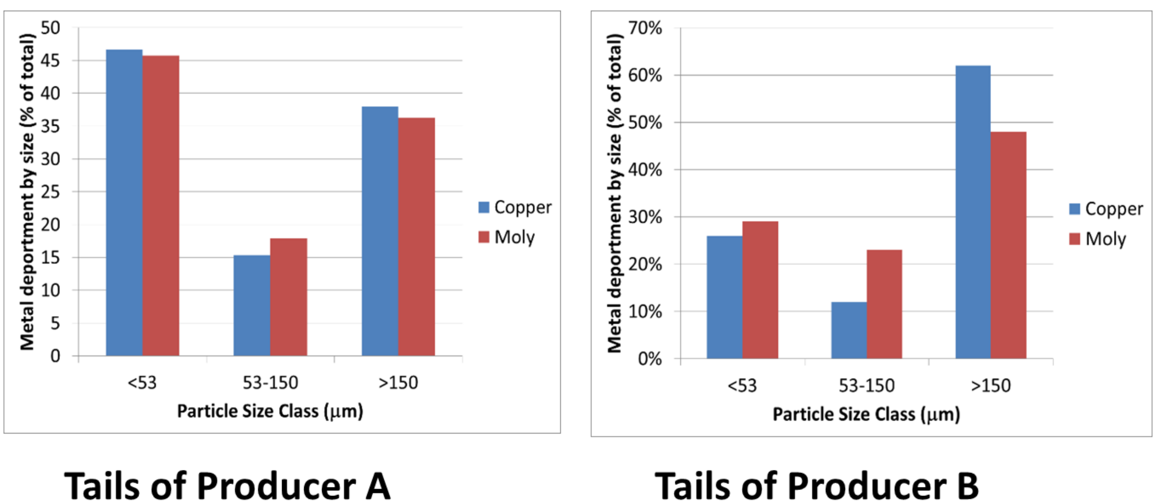

Figure 1. Metal contained in final tailings by size for two major copper concentrators

A simplified way to look at the transport phenomena that occurs in the flotation process is shown as Equation 1. The overall process is a combination of kinetics and mass transfer. The rate of the first step is often represented as being of first order, driven by collisions and therefore following the law of mass action (i.e., ore disappears from the pulp in proportion to its concentration). 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 understanding that the efficiency of bubble-particle collisions, especially for fine particles, is increased by their kinetic energy. The first reaction is also represented as being reversible, meaning that the bubble-particle aggregate, which can float out of the pulp, is not a final product, but actually an intermediate. 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. An example of this was shown through a very elegant experimental set up (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. The second process will predominate over the reverse reaction in a low energy fluid environment.

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

Equation 1 provides 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 or coarser. For conventional mechanical cells, both of these reactions in Equation 1 occur at the same time and in the same unit. 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 conventional 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. That is the reason why the flotation efficiency of fine and coarse particles cannot be simultaneously improved, as shown in Figure 1.

This dilemma can be resolved and Equation 1 can be optimized if we allow the forward component of the first reaction of Equation 1 and the second reaction to occur in two distinct 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 unit to maximize froth recovery. Essentially, the two main processes have been de-coupled and Equation 1 can be re-written as a non-reversible high energy particle collection step, followed by a low energy froth recovery step, as shown in Equation 2.

$$\text{Bubble + Particle} \xrightarrow{\text{attachment}} \text{Bubble-particle aggregate} \xrightarrow{\text{transport to launder}} \text{Recovered particle} \qquad (2)$$

Unit 1 (particle collection) | Unit 2 (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, consists of a rotor-stator configuration, which mixes the feed slurry and air with extreme energy. The feed travels from the bottom to the top, with a residence time distribution that is designed to approximate a plug-flow in a highly turbulent mixing environment with short residence time, on the order of several seconds. The internal tank is hydraulically isolated from the main tank on all sides except through a gap between the side walls and a rotating lid on the top of the vessel. Aerated pulp is pushed through the annular gap between the rotating lid and internal tank wall, based on a small positive pressure between the tanks. This configuration creates ideal conditions for bubble-particle collection in the internal tank. The tanks are effectively isolated, so that the second tank can be operated without any mechanical agitation and acts purely to separate the bubble-particle aggregates into a froth phase, which is recovered in a launder. The lack of mixing in the outer tank also allows the effective use of wash water, which can be used to reject hydraulically entrained gangue in the concentrate.

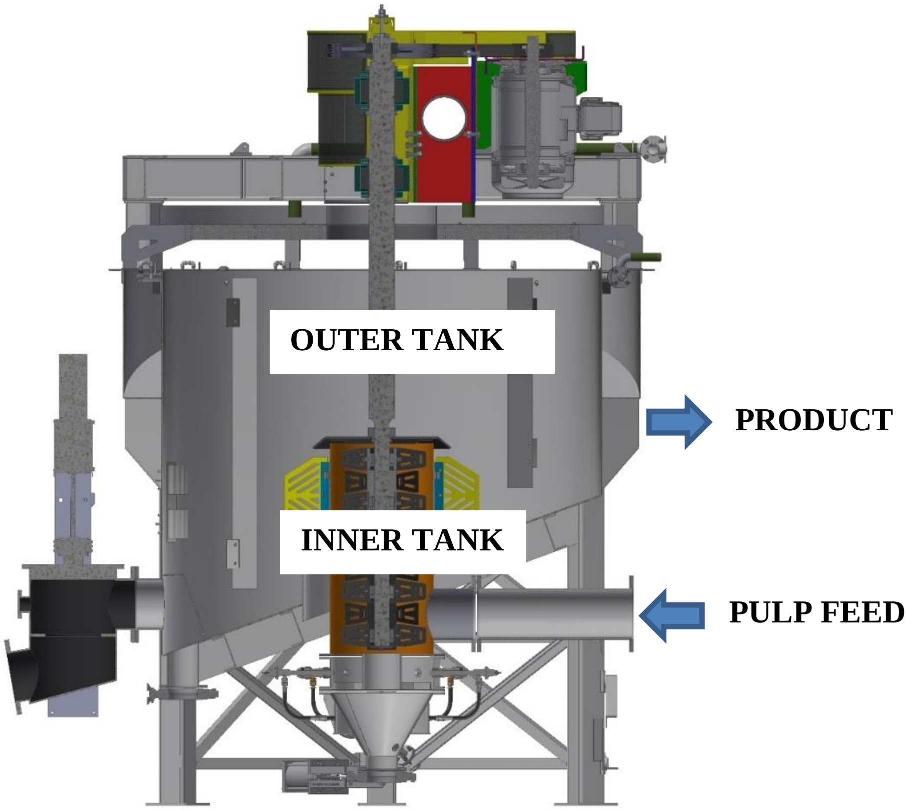

Figure 2. A StackCell cut-away showing the concept of a tank within a tank. The concentric inner tank where particle collection occurs as well as the outer tank, where particle recovery occurs are shown.

Quantifying the total requirement for flotation volume is essential for evaluating different flotation technologies as well as sizing flowsheets and concentrators for a particular ore feed and concentrator name-plate capacity. The flotation volume depends on the overall unit-averaged flotation rate, which is essentially the kinetic rate of the two-step process shown in Equation 1. If the rate of this reaction can be doubled, while achieving comparable enrichment and recovery, then the size of the flotation equipment can be reduced by half. And more significantly, all of the ancillary equipment and the plant layout can be reduced as well.

An industry standard for comparing kinetics and sizing mechanical cells is the 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. A vast amount of empirical data has shown that the predicted response of large cells can be well approximated by multiplying the cumulative time axis 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.

In the following two case-studies, flotation rates for two StackCell configurations are compared with each other, with conventional mechanical cells and with the Denver batch lab tests results. In the first case, a train of three 0.6 metre diameter StackCells are run side by side with a train of conventional mechanical rougher cells in a large copper concentrator (Wasmund, 2018). In the second case study, a 3 metre diameter StackCell is run in a nickel cleaner application. In both cases, significant improvements in the unit averaged flotation rate are observed.

EXPERIMENTAL

A: First case study: a copper rougher application

In this study, a train of three 0.6 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 of the conventional cells 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.

Figure 3. The train of three 0.6 metre diameter StackCells used in this pilot study.

The StackCell train was fed from the same feed as the production roughers. A sieve bend was added as a trash screen, and the tank was provided to ensure steady flowrate, as shown in Figure 4. After any changes in process inputs around the StackCells, the system was left untouched for 15 minutes before taking a sample cut, and additional 15 minutes were allowed before the second and third cut. It is noteworthy that although the StackCell can run effectively with wash water, it was not used for any of these rougher tests. 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. 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.

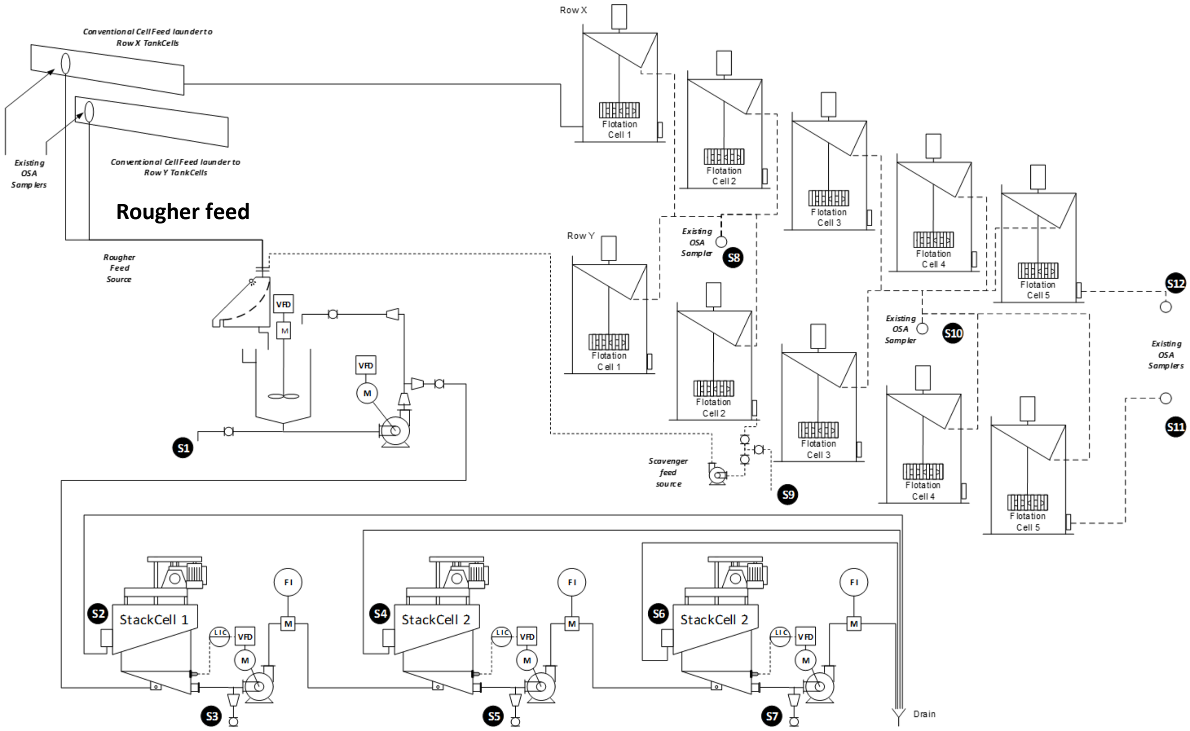

Figure 4. Block diagram showing the experimental configuration for these pilot plant campaigns

B: Second case study: a nickel cleaner application

A second case study of an industrial scale StackCell, as shown in Figure 2, will now be explained. This is a 3 metre diameter unit, treating nickel sulfide concentrate in the first cleaner position of a production facility. The 80th percentile of the particle size in the feed stream was 35 microns, and the percent solids was 6% by weight. The volumetric feed-rate of this StackCell was varied between 500 and 780 m^3/hour of slurry, corresponding to a retention time of 2-3 seconds in the inner tank and 65 to 105 seconds in the overall StackCell. Wash water was used for this operation. To compare the kinetics of the StackCell, similar feed was collected and run on a two litre Denver lab batch test. This allowed a direct comparison of the StackCell kinetics with the Denver lab test.

RESULTS

A: First case study: a copper rougher application

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 for five sets of StackCell tests (annotated A-E in Figure 5), and the mass balances were reconciled as explained in the Experimental section. During the same experiment, 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, the kinetic response curves for the 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 and outer tank. In Figure 5B, 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. For comparing the flotation rate of two different devices, it is important to show that the grade and recovery is comparable for each case, in other words, the rate is being compared for the same metallurgical end-point. To ensure that the end-point of the flotation was comparable for the StackCells, the conventional cells and the Denver cells, the total recovery and cumulative grade are shown in Table 1.

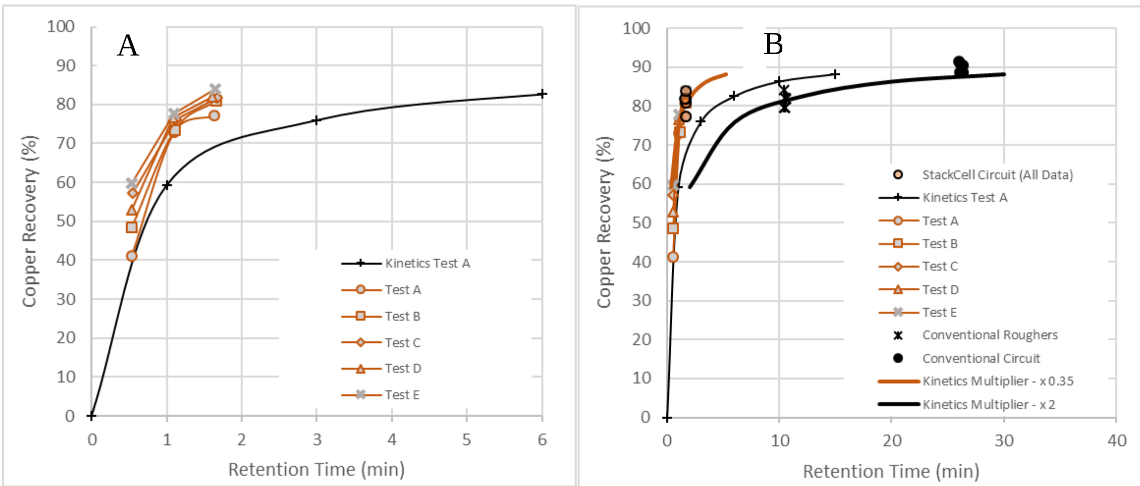

Figure 5. Rougher kinetic responses for five tests conducted on a StackCell train in parallel with production mechanical cells and a Denver batch test, all receiving the same feed

Table 1. Average flotation parameters for copper rougher benchmarking campaign (case study 1)

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

B: Second case study: a nickel cleaner application

In this case-study, the StackCell configuration consisted of a single 3 metre diameter StackCell. The unit was sampled on the inlet, concentrate and tail, and a least squares algorithm, similar to the one described for the first case study was used to reconcile the experimental data. A sample of the feed with a comparable composition from the same campaign was measured with a Denver lab test. The Denver test was run twice to obtain replicates and the averaged data was used. The results are shown in Table 2 and Figure 6. The StackCell data was taken from a campaign of tests where the operating parameters and feed rates were being systematically manipulated in order to optimize performance. The data set included variation in reagent dosage, froth level, wash water, air addition, rotor speed and percent solids. To ensure that the Denver test and the StackCell recoveries were being compared for a similar end-point on the grade recovery curve, only the industrial StackCell data was taken for data-points where the grade was within the range of cumulative grades obtained in the Denver tests (10.4–12.8% nickel).

The results in Figure 6 again indicate that the 2-stage StackCell has accelerated kinetics compared with a Denver batch test. The variation in the StackCell performance, explained above, was caused by variation in operating parameters, which may have had second order effects on the flotation rate, however a definite trend is still apparent. The centroid of the StackCell data in Figure 6 is 32.0% recovery at 1.5 minutes of retention time based on 8 observations. A horizontal tie-line (shown as a hatched red line in Figure 6) connecting the centroid of the StackCell data intersects the Denver rate curve at approximately 3.6 min and another horizontal tie-line (shown as a hatched black line) intersects the hypothetical curve for mechanical cells at approximately 7.2 min (based on the 2x rule). This means that the 3 metre diameter StackCell should be able to achieve the same flotation performance as a conventional mechanical cell in approximately 21% of the volume (1.5/7.2 = 21%). Considering that the 3 metre StackCell has about 15 m^3 of volume, this means that it should be able to achieve the same metallurgical performance as a conventional cell of approximately 70 m^3.

Table 2. Average flotation parameters for nickel cleaner benchmarking case-study (case study 2)

Flotation type	Cumulative Recovery (%)	Combined Grade (%Ni)	Time (min)
Denver lab test	8.7	11.0	1.0
Denver lab test	14.6-19.8 (average 17.2)	10.88-12.80 (average 11.8)	2.0
Denver lab test	28.4-35.6 (average 32.0)	10.67-11.43 (average 11.1)	4.0
Denver lab test	39.6-49.0 (average 44.3)	10.4 (average 10.4)	6.0
3 metre StackCell	28.3	12.6	1.8
3 metre StackCell	31.8	11.6	1.8
3 metre StackCell	34.8	12.5	1.5
3 metre StackCell	35.0	12.7	1.5
3 metre StackCell	34.9	11.1	1.5
3 metre StackCell	34.0	11.0	1.5
3 metre StackCell	33.5	12.5	1.5
3 metre StackCell	25.7	12.4	1.1

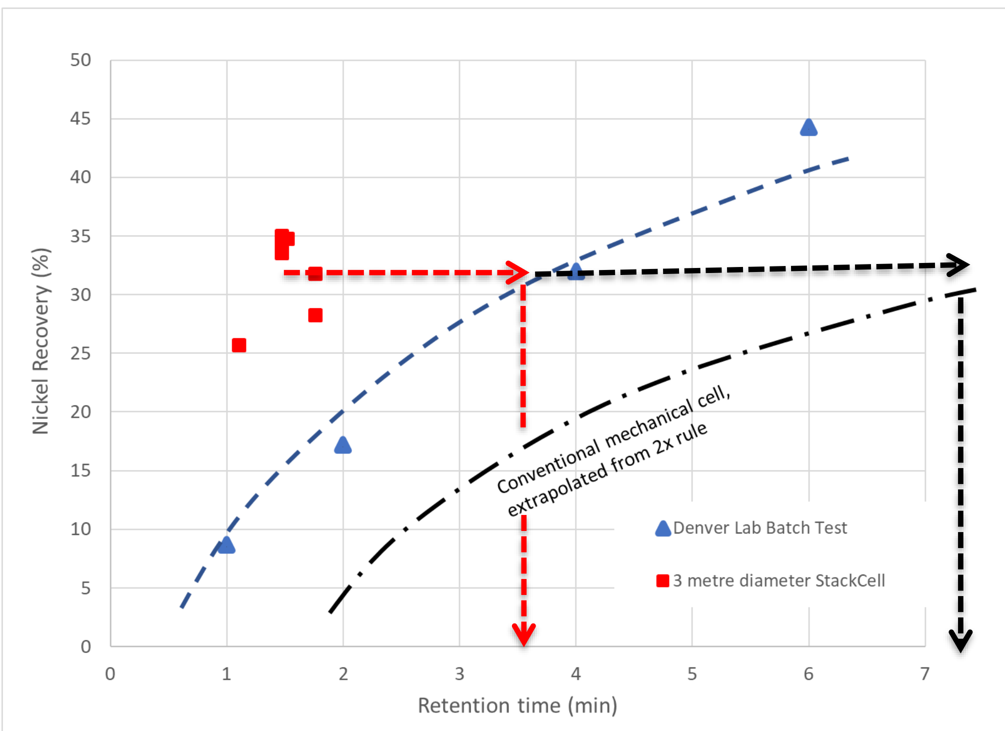

Figure 6. Cleaner kinetic responses for a single 3 metre diameter StackCell and a Denver batch test, based on the same feed

DISCUSSION

The combination of case 1 and case 2 show the performance of the StackCell in two important but very different industrial base-metal flotation applications. In the first case, it was demonstrated that the StackCell can operate in a rougher duty, with relatively coarse feed, and that it can operate in multiple stages, as required in all rougher circuits. This test-work also confirmed the “2x scale-up rule” that conventional mechanical cells are about half as fast as the kinetics of a Denver test. Moreover, the StackCell pilot units achieved similar metallurgical performance as the conventional mechanical cells (grade and recovery) with about 18% of the required time of conventional mechanical cells and about 35% of the time required in a Denver lab test.

In the second case, while only a single StackCell stage was studied, this was a large-scale unit (3 metre diameter with approximately 15 m^3 of volume) and it was confirmed that the flotation rate is significantly improved compared with the standard Denver test. To achieve an end-point of approximately 32% recovery, the StackCell used 42% (1.5 min/3.6 min) of the residence time required for a lab Denver unit. This is fairly similar to the value of 31% reported for roughers in the first case study and clearly demonstrates that the accelerated kinetics of the StackCell are scalable to industrial sizes. Both of these results show that StackCells up to 3 metre in diameter should be expected to be five times faster than conventional mechanical cells.

Table 3. Summary of flotation rate benchmarking; StackCell, Denver batch test, and conventional

StackCell demonstration	Scale	Acceleration compared with Denver	Acceleration compared with conventional mech cells
Copper rougher	0.6 m diameter	2.9x	5.7x
Nickel cleaner	3.0 m diameter	2.4x	4.8x*

* Extrapolated from 2x scaling rule

SUMMARY AND CONCLUSIONS

Two-stage flotation as demonstrated by Eriez’ StackCell provides accelerated flotation kinetics, which has now been confirmed in industrial settings and at scales up to 3 metre diameter. This includes tests for base metal sulfides on rougher and cleaner applications. The improved flotation rate is attributed to being able to operate two stages within each unit, each optimized for a single step in the flotation process. This allows the unit to operate with efficient high energy particle collection and simultaneous quiescent froth separation with minimized drop-back. The Denver lab test is a useful scale-up method for industrial StackCells, but a scaling factor of 0.3 to 0.4 is more appropriate, compared with 2.0-2.5 for conventional mechanical cells. This means that StackCell flotation circuits could be as productive from a metallurgical perspective as conventional units that have 5-6 times the combined working volume.

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