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Improving fine particle flotation using the StackCell™ (raising the tail of the elephant curve)

M.J. Mankosa[a,*], J.N. Kohmuench[b], L. Christodoulou[c], E.S. Yan[c]

[a] Eriez Manufacturing Company, 2200 Asbury Road, Erie, PA 16506, USA
[b] Eriez Magnetics Pty Ltd, 21 Shirley Way, Epping, Victoria 3076, Australia
[c] Eriez Flotation Division – USA, 1901 Wager Road, Erie, PA 16509, USA

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ABSTRACT

For decades, the conventional flotation machine has been the accepted tool for processing sulfide ores. As plant capacity increases, machine size has evolved to as much as 600 cubic meters to keep pace with the required retention times. However, the excessively large size of these machines requires extreme floor space, foundations and power to operate. Recent work conducted by Eriez has shown that high-efficiency flotation machines which are based on focused energy input can achieve similar results with significantly less retention time, floor space and power. Comparable performance is achieved through intense contacting in a separate chamber which provides concentrated energy input focused specifically on bubble/particle interaction. When compared to conventional technology, data show that this novel approach can achieve the same recovery as a mechanical cell in a fraction of the residence time. This paper will discuss the theory of operation of the StackCell™ and present data from various lab- and pilot-scale test programs.

1. Introduction – present day flotation practices

Concentration of fine particles using froth flotation has been practiced for well over a century. Extensive fundamental research has been conducted on all aspects of the chemistry and hydrodynamics of the flotation process. As defined early on by Gaudin et al. (1931), the process is particularly successful when applied to a particle size range of approximately 15–150 µm. This early work, presented as the well-known "Elephant Curve" (Fig. 1), shows a clear drop-off in flotation performance outside of this range. The decline on the coarse end is typically attributed to excessive turbulence, buoyancy limitations and particle drop-back from bubble coalescence in the froth. The latter has been shown to result from competition for the available bubble surface area. Recent work show that coarse particles are indeed floatable (Gontijo et al., 2007) and that the recovery limitations realized in industry can be overcome through novel machine designs specifically tailored for coarse particle flotation (Mankosa et al., 2016c).

The reduction in flotation recovery for fine particles has been well documented over the past decades (Flint and Howarth, 1971; Fuerstenau, 1980; Luttrell, 1986, Miettinen, 2007) and is attributed to reduced collision rates and poor adhesion characteristics. A great deal of research was focused on fine particle flotation with advancements made through improved hydrodynamics. One of the most significant improvements was development of microbubble flotation for fine particle recovery (Yoon et al., 1988). This work, however, was generally focused on column cells for coal and industrial minerals. As such, there has been no significant advancements to extend the "tail" of the elephant curve for sulfide applications. In fact, size-by-size deportment data collected from the tailings streams of currently operating plants show that a significant amount of value still resides in the finest fraction that is discarded as refuse (Mankosa et al., 2016b).

Since the beginning of this millennium, flotation machine manufacturers have focused on increased cell size. This trend is clearly shown by the data presented by Noble (2012) and reproduced in Fig. 2. These results show an approximate fivefold increase in machine size every 20 years; culminating with an increase from 100 to over 660 cubic meters since the turn of the century. This dramatic increase in size has clearly been driven by operator's desires for fewer, high-capacity machines - resulting in a simplified plant layout and reduced maintenance. Unfortunately, the increase in size can be contrary to cell performance. Larger machines require increased energy input to maintain particles in suspension. The increased energy input results in greater turbulence which is a major contributor to the loss of recovery for coarse particles. Likewise, the size and reduced number of cells in series can result in an increase in by-pass or short-circuiting of material; this having a negative effect on the slower flotation species (i.e., fines). The large cells are

* Corresponding author.
E-mail addresses: mmankosa@eriez.com (M.J. Mankosa), jkohmuench@eriez.com (J.N. Kohmuench), lchristodoulou@eriez.com (L. Christodoulou), eyan@eriez.com (E.S. Yan).

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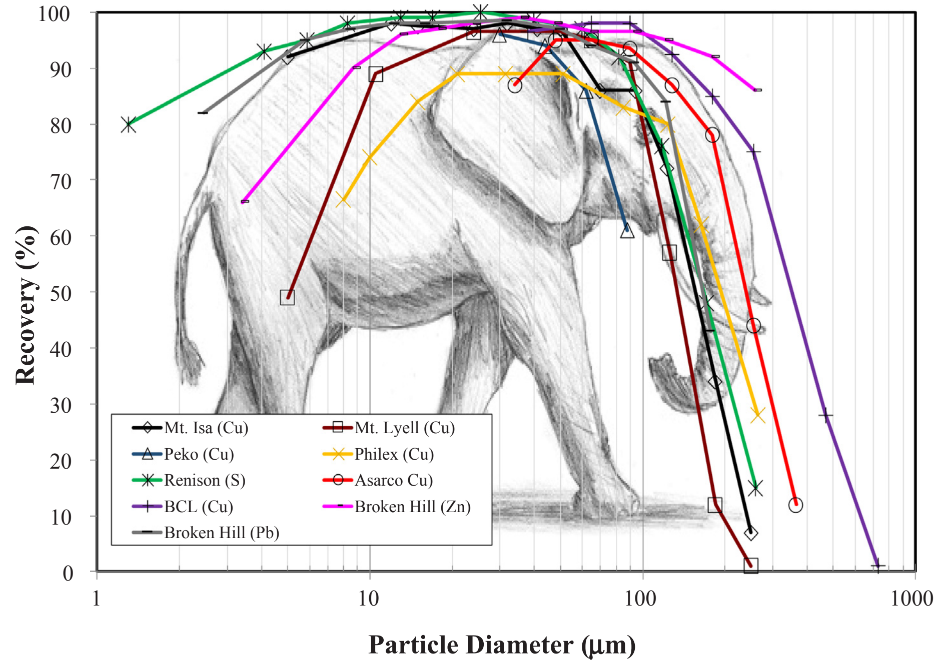

Fig. 1. Conventional flotation data for industrial sulfide flotation circuits (after Lynch et al., 1981).

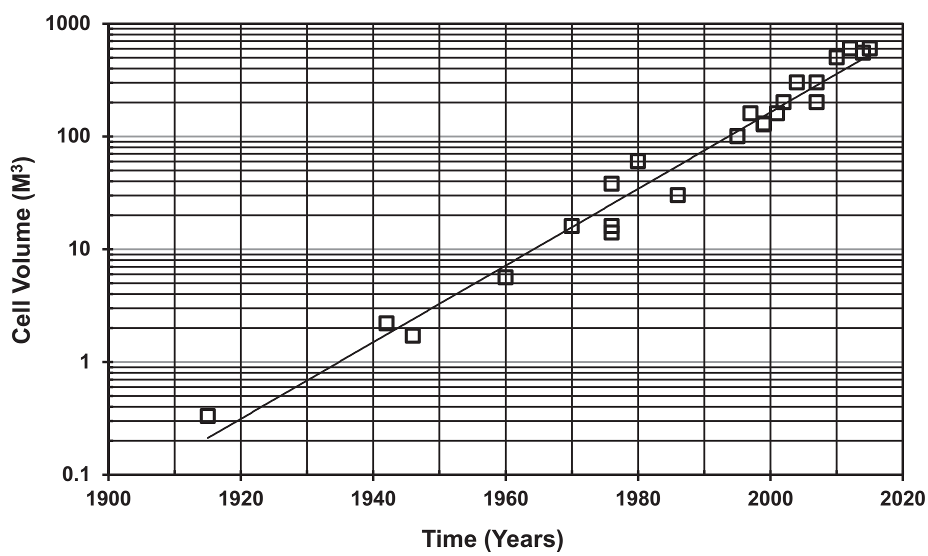

Fig. 2. Growth in conventional flotation cell volume over the past century (Noble, 2012).

also more energy efficient in that the total energy per unit volume is reduced. However, this is contrary to previous work which has shown that high specific energy input is required to improve the flotation kinetics of fine and/or slow floating particles (Mankosa et al., 2016a).

With input from major engineering houses and end-users, Eriez Flotation Division (EFD) developed the StackCell™ technology with the goal of providing a more efficient flotation option. This device builds on the concept of focused energy input to enhance fine particle recovery as well as improving flotation kinetics in the "sweet spot" of the elephant curve. This novel, patented approach de-couples the particle contacting zone within the cell from the phase separation process. As a result, overall unit size can be reduced by an order of magnitude while maintaining the same capacity and metallurgical performance. The implications of this step-change in technology are numerous and include a significant reduction in energy consumption (> 40%) as well as reductions in plant height, footprint and foundation loads of greater than fifty percent.

A schematic of the StackCell™ is provided in Fig. 3. During operation, feed slurry is introduced to an aeration canister through a side (or bottom) feed port. At this point, low pressure air is added to the feed slurry. The air and feed slurry then travel up into the aeration chamber where significant shear is imparted to the system. The shear forces imparted to the aerated slurry are used to create small bubbles and for bubble-particle contacting. In fact, all of the bubble-particle collisions occur in the aeration chamber prior to discharge into the outer tank. Once the slurry enters the outer tank, a phase separation occurs between the froth and pulp. The pulp level is maintained through the use of a level sensor and underflow control valve. The froth depth is maintained sufficiently deep to facilitate froth washing which minimizes the entrainment of fine hydrophilic gangue. The froth overflows into a froth collection launder.

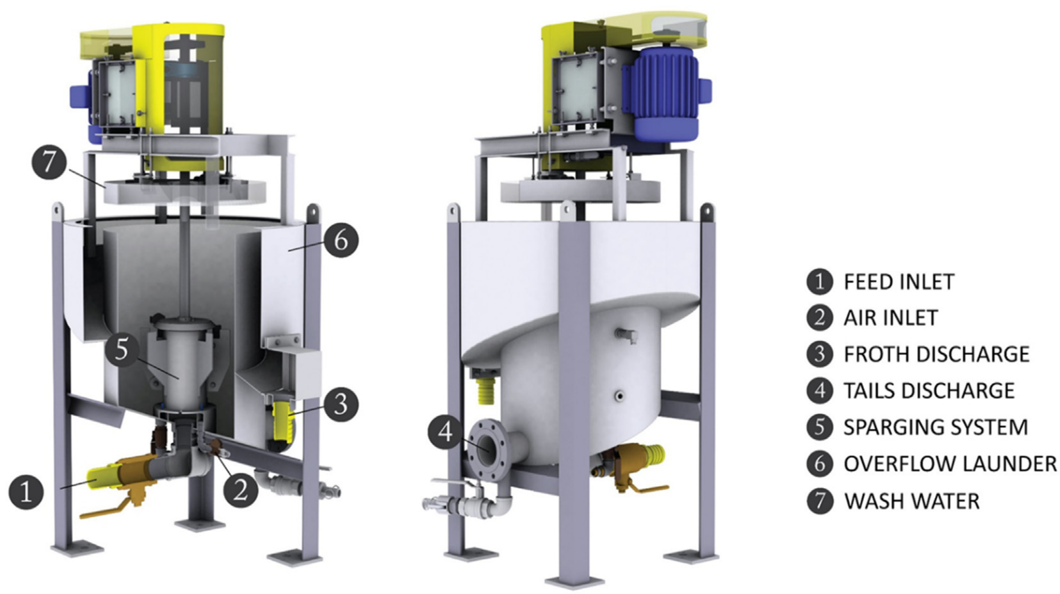

Fig. 3. Cutaway schematic of the StackCell™ technology.

2. Theory

The StackCell™ technology was designed based on optimization of the known parameters governing flotation such as flotation rate, retention time and mixing conditions. Additional goals included reduction in overall energy consumption, column-like metallurgical performance and a reduction in plant volume (floorspace and height). The primary objectives were to improve process kinetics for all particles finer than 150 µm as well as extend the bottom limit of the elephant curve to more effectively recover particles finer than 15 µm. Of course, these goals had to be achieved while taking into consideration operating issues such as power and maintenance.

Examination of the governing relationship for a process reaction (Eq. (1)) shows that the rate (k), retention time (τ) and mixing conditions (Pe) are the main contributors to particle recovery in a flotation system, where

$$R \propto k\ \tau\ Pe \tag{1}$$

Each of these parameters have been exhaustively studied by various researches over past decades. Work by Yoon and Luttrell (1989) and others has shown that a decrease in bubble size has a dramatic positive influence on flotation rate. Likewise, it is obvious that an increase in process retention time will also improve recovery. Less obvious is the effect of mixing conditions on overall system performance. Prior work has shown that, all things being equal, more plug-flow systems (higher Pe values) will provide a higher process recovery. One means to achieve this is to increase the number of tanks in series for a given process rate and retention time. This point has been highlighted in past work (Mankosa et al., 1992) and is illustrated in Fig. 4 which shows the influence of more plug-flow conditions (higher Pe value) on recovery as a function of retention time.

Unfortunately, there is a practical limit to the number of tanks which can be considered for a given application. Likewise, increasing the size of the tank to expand retention time is a costly approach from both a capex and opex point of view. The obvious, but non-trivial, approach is to improve the process rate. To achieve a substantial increase in flotation rate, the StackCell™ incorporates a unique, high-shear, bubble-particle contactor in lieu of the conventional rotor–stator mechanism historically utilized in mechanical float cells. Instead of operating with a large tank volume, the StackCell™ forces the bubbles and particles to contact within a small aeration chamber which is mechanically isolated from the remainder of the tank.

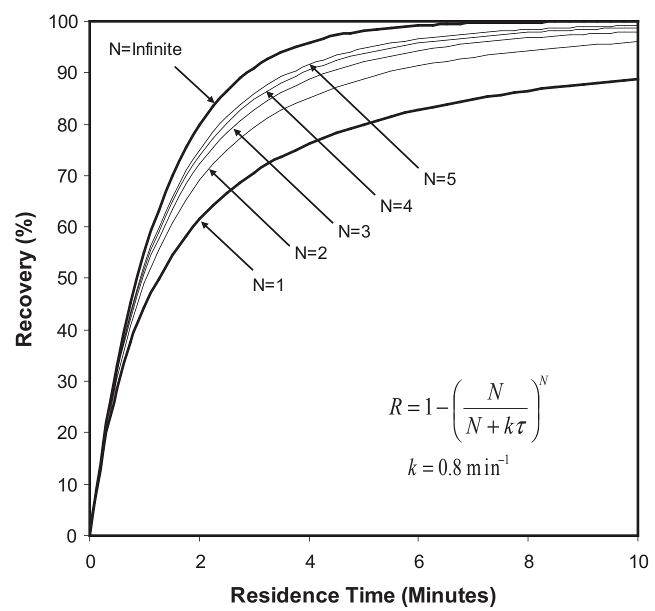

Fig. 4. Process recovery as a function of retention time showing the transition from perfectly mixed to plug-flow conditions.

As seen in Eq. (2), in a highly turbulent environment, the flotation rate constant (k) can be expressed as:

$$k \propto C_b C_p E \tag{2}$$

where C_b is the concentration of bubbles, C_p is the concentration of particles, and E is the specific energy imparted to the system (Williams and Crane, 1983). The intense shear environment within the aeration chamber provides an energy dissipation level that is substantially higher than that produced by conventional flotation machines, thereby increasing the process rate and enhancing overall particle recovery. The contactor is specially designed to efficiently impart energy for bubble-particle contacting and to avoid unnecessary pumping or unwanted recirculation of the feed slurry. This allows the energy input to be used solely for gas dispersion and contacting and not for particle suspension as in the case with conventional cells. Moreover, the intense mixing shears the low-pressure air blown into the machine into extremely small bubbles which substantially increases the concentration of bubbles

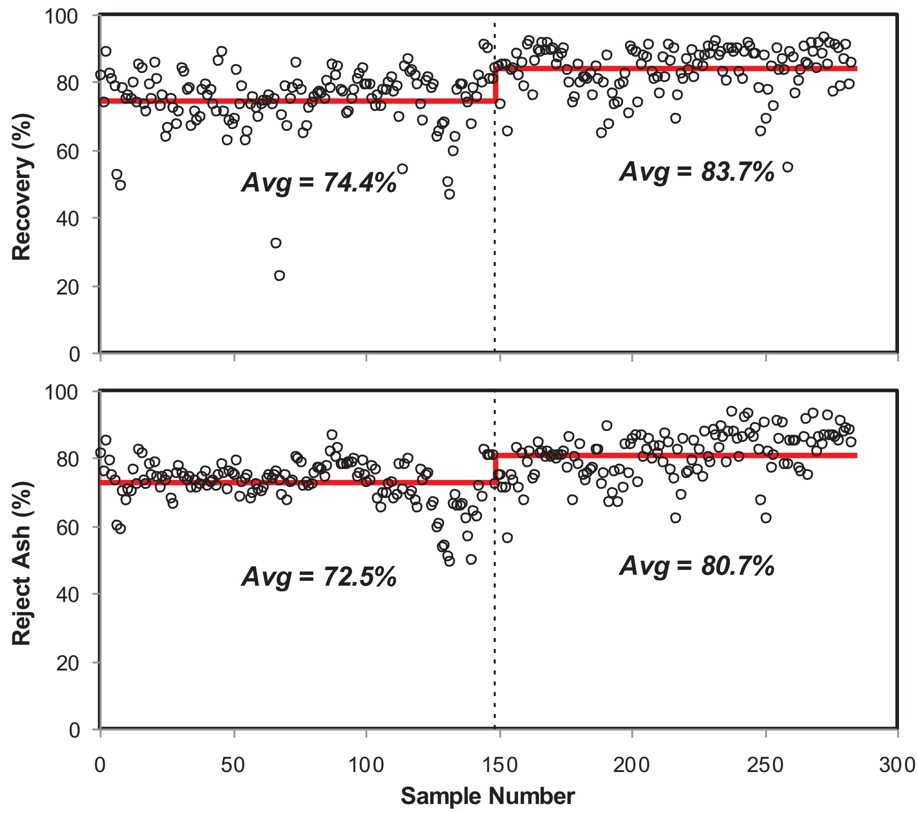

Fig. 5. Change in flotation circuit performance due to the installation of the StackCell™ technology (dashed line represents the sample where the changeover occurred).

present in the contacting chamber. This feed pre-aeration approach ensures that the maximum concentration of floatable particles and bubbles are present during the contacting phase of the flotation process.

3. Industrial applications

3.1. Full-scale application in U.S. coal

Early work with the StackCell™ technology was conducted throughout the eastern U.S. coal fields and has been reported in numerous publications (e.g., Kohmuench et al., 2008). This work clearly showed improved performance due to enhanced process kinetics and led to an early full-scale demonstration of the technology at an industrial coal preparation plant. The plant processed run-of-mine coal from several seams supplied by both underground and surface mines. The single 3.7-meter diameter StackCell™ was installed as a scalping system ahead of two existing flotation columns. Historical data suggested that the two column cells were often overloaded due to plant production demands. The tailings stream from the StackCell™ was equally split and fed to the two existing columns.

Fig. 5 shows the impact of the StackCell™ installation on the combustible recovery and refuse ash for the entire flotation circuit. For the first 149 production samples taken prior to the installation, the two column cells provided an average recovery of 74.4% and a combined refuse ash of 72.5%. After the installation, the combined recovery for the StackCell™ and two column cells improved to 83.7% and the refuse ash increased to 80.7%. The increased recovery is significant considering that less than 10% more cell volume was added to the circuit via the installation of the StackCell™ technology. In fact, the aeration chamber provided an additional residence time of less than five seconds to the total flotation circuit. The success of this application led to multiple installations of the StackCell™ technology throughout the U.S. coal industry.

3.2. Pilot-scale testing in sulfide applications

3.2.1. Test circuit and sampling procedures

Based on the success achieved in the U.S. coal industry, an in-plant test program was initiated at a large-scale copper sulfide operation. The existing plant utilizes multiple conventional SAG/ball mill circuits for size reduction followed by several parallel lines of conventional flotation cells to produce a bulk copper/molybdenite concentrate which is subsequently cleaned in column cells and further processed to make separate copper and molybdenite concentrates.

For this test program, three pilot-scale StackCells™ were installed in series next to a line of five commercial 300-cubic meter tank cells. The first two tank cells are configured as roughers and the subsequent three cells are configured as scavenger cells. The bank is set-up such that the combined rougher concentrate (first two cells) and the second cell tailings can be sampled to determine metallurgical performance of the rougher cells. Likewise, combined scavenger concentrate (last three cells), circuit final tailings and rougher tailings/scavenger feed samples can be collected to determine performance of the scavenger circuit.

The StackCells™ were set-up to operate in series and were configured to accept feed from either the rougher or scavenger cell feed from the full-scale circuit. The feed samples were continuously discharged into a 6- cubic meter sump equipped with a mixer and variable-speed centrifugal pump. The latter was used to recycle a substantial portion of the feed to improve homogeneity of the sample. A bleed stream was installed in the recycle loop to deliver feed to the pilot StackCells™. Electronic metering pumps were used to add flotation reagents to the feed sump as required. Each flotation cell was set-up with a separate pump for level control and to convey feed to the subsequent unit. This option was selected over standard tailings discharge valves to allow the cells to be located at different positions/elevations in the plant if necessary. Additionally, rotor speed and air, water and tailings flow rates were controlled/measured for each cell. The test circuit was configured to allow for independent sampling of feed, product and tailings streams

Fig. 6. Feed sump/pump arrangement and three-stage StackCell™ test circuit.

for each cell. A photo showing the StackCell™ test circuit is shown in Fig. 6.

Based on the configuration of the full-scale circuit, a unique opportunity existed to sample the full-scale circuit simultaneously with the test circuit. Two parametric test campaigns were established to evaluate both rougher and scavenger feed. Critical operating parameters were identified and included retention time, air flow rate, reagent addition and impeller speed. In all cases, samples were collected from the full-scale and pilot circuits. All slurry flow rates were measured for each pilot-scale test. Samples from both circuits were evaluated for percent solids and submitted for assay for copper, iron, molybdenum and sulfur. Operating data for the full-scale tank cells was recorded from the plant control system for each test. Mass flows and analytical data were material balanced to ensure consistent data sets.

3.2.2. Test results

The primary objective of the test program was to determine whether the advanced kinetics seen in the coal industry would translate to sulfide applications. Coal is very strongly hydrophobic in nature and fast flotation kinetics are typically observed across all size classes. As shown in Fig. 1, this is not necessarily the case for sulfide applications as the finer fractions (< 15 µm) often do not respond well to conventional flotation. Additionally, longer retention times (> 20 min) are required to achieve acceptable recovery. As such, there was an outstanding question as to whether the StackCell™ would achieve acceptable recovery in the latter stages. To evaluate this concept, results were initially analyzed on a stage-by-stage basis for both rougher and scavenger feed. These findings, shown in Fig. 7, are indicative of a higher flotation rate as substantial recovery is achieved in each stage at a very short retention time as compared to the conventional cells. In each case, copper recovery increased from the first to the last cell in the circuit.

Overall circuit recovery for these tests is shown in Fig. 8 in comparison to that simultaneously achieved in the full-scale rougher and scavenger circuits. For the pilot-scale rougher tests, the average copper recovery was 77.8% as compared to the full-scale rougher circuit recovery of 78.3. Likewise, the pilot-scale scavenger circuit copper recovery averaged 26.7% as compared to 27.0% for the full-scale circuit. In both cases copper grade was comparable. As will be shown later, this result was achieved at a significantly shorter circuit retention time.

Having demonstrated comparable stage-by-stage recovery and metallurgical performance to the existing tank cells, tests were undertaken to evaluate the StakeCell™ kinetics. Tests were conducted as a function of feed rate utilizing both the rougher and scavenger feed sources. As with prior tests, samples were simultaneously collected from the pilot- and full-scale circuits for evaluation. Additionally, samples were also collected from each feed stream and submitted to a third-party laboratory to conduct standard bench-scale kinetics tests. The results from these tests, shown in Fig. 9, clearly illustrate the advanced kinetics demonstrated by the StackCell™ technology. For the rougher application, each circuit achieved copper recoveries ranging from 60 to 85%. However, the tank cells required approximately a 6-fold longer retention time to achieve the same result as the StackCell™. Likewise, comparable recoveries were achieved for the scavenger tests with a 9-fold shorter retention time.

As part of the rougher and scavenger retention time tests, samples were also collected for laboratory kinetics tests. The samples were submitted to an independent, third-party lab for testing and sample analysis. The results from these tests are also included in Fig. 9. The laboratory kinetics test is globally recognized as the "gold standard" for benchmarking flotation performance. Projection for full-scale machine design is typically based on a multiplier (2–2.5 ×) of the retention time achieved from this lab test. In this case, it is interesting to note that for the rougher application, the StackCell™ performance exceeded the laboratory kinetics test. To achieve a copper recovery of 80%, the kinetics

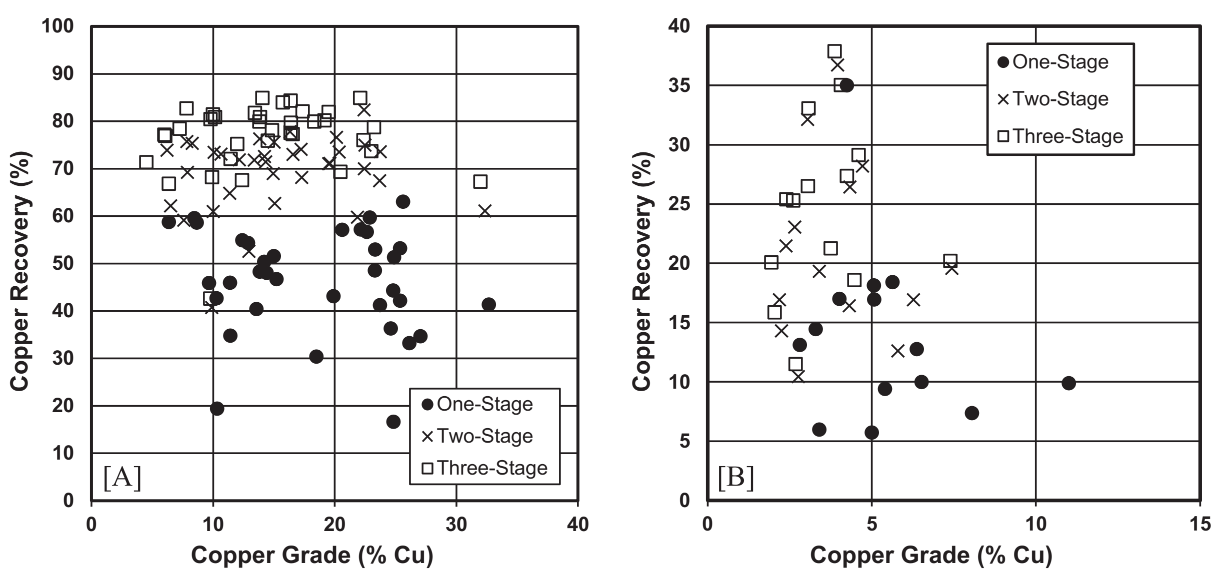

Fig. 7. Stage-by-stage copper recovery versus product grade for rougher [A] and scavenger [B] feed for pilot StackCell™ circuit.

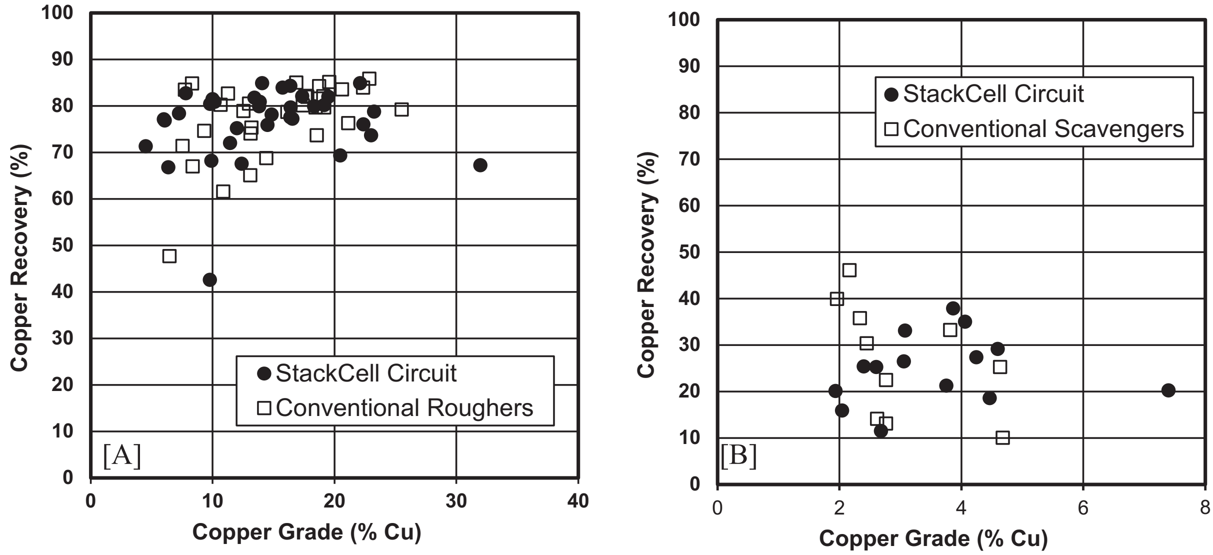

Fig. 8. Copper grade versus recovery results for rougher [A] and scavenger [B] feed streams.

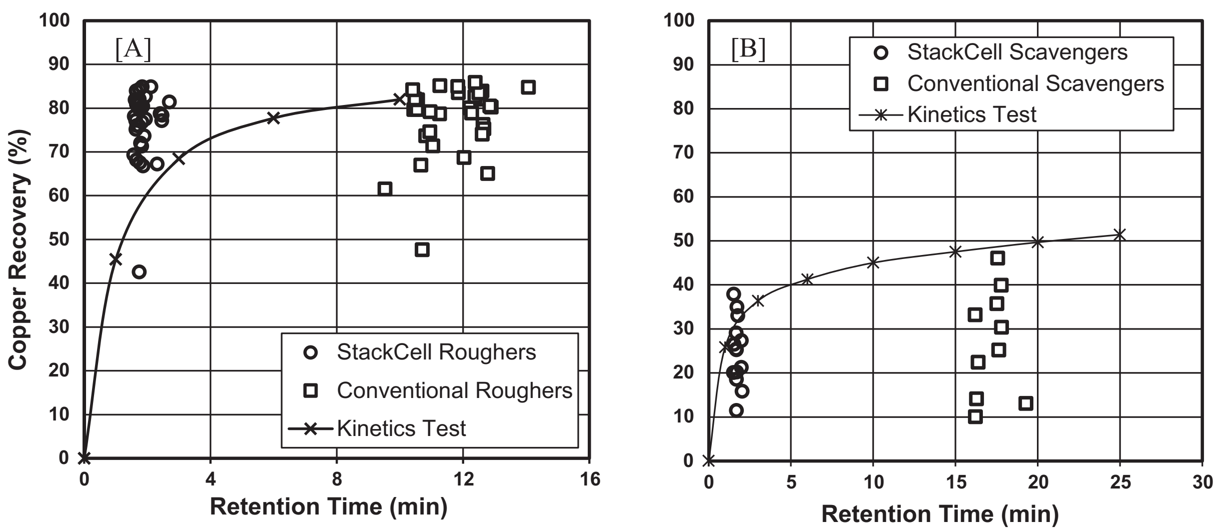

Fig. 9. Pilot- and full-scale circuit copper recovery as a function of retention time for [A] rougher and [B] scavenger feeds.

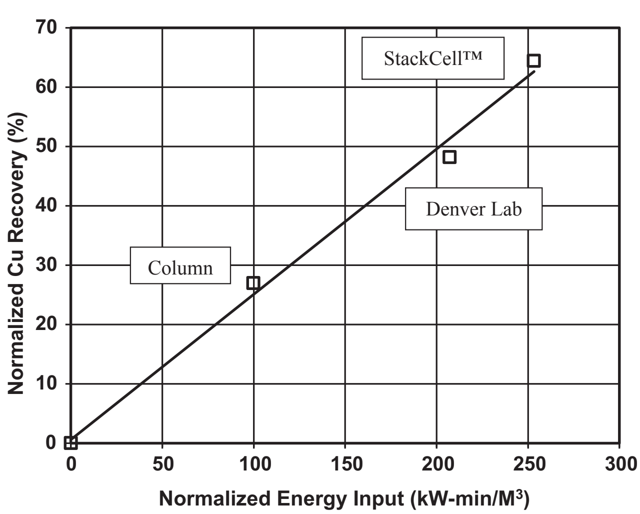

Fig. 10. Copper recovery as a function of normalized energy input for various flotation machines.

test indicates that a retention time of approximately 8 min is required. The pilot results indicate that the StackCell™ circuit could achieve this result in two minutes. This represents a fourfold increase in process kinetics. While not as dramatic, similar results are shown for the scavenger feed tests as well, achieving copper recoveries in approximately the same retention time as the lab kinetics test.

The StackCell™ is designed to provide an extremely focused energy input per unit volume of feed. This point is reinforced by the data presented in Fig. 10 which show normalized copper recovery as a function of the cell energy input. The latter is normalized for both cell volume and average retention time. Normalized copper recovery is determined by dividing the copper recovery at the given retention time by the projected copper recovery at infinite retention time. This calculation was performed using pilot-scale column and StackCell™ data as well as lab-scale conventional flotation tests. This analysis clearly shows the energy density of the StackCell™ exceeds even a lab-scale conventional flotation cell. Although the normalized energy is high, the absolute energy input to the system is significantly less than a full-scale convention cell since the active volume of the contacting zone is minimal. In fact, a recent comparison of a full-scale StackCell™ with 300-cubic meter conventional cells shows an overall energy savings of 60% to achieve the same overall plant capacity.

4. Summary and conclusions

A new high-capacity flotation technology, the StackCell™, has been developed as an alternative to both conventional and column flotation machines. This technology makes use of pre-aeration in a high-shear aeration chamber that provides efficient bubble-particle contacting, thereby substantially shortening the residence time required for flotation. Based on results obtained in this test work, an engineering study was undertaken to compare the StackCell™ and conventional tank-cell technology at an equivalent capacity and metallurgical performance. Consideration was given to total energy consumption, plant space requirements and capital/operating costs. The major conclusions from this evalution are summarized below.

Capital costs – The StackCell™ offers a 40–50% savings in capital cost (flotation equipment and blowers) as compared to conventional flotation due to the substantially smaller tank required.

Power consumption – Power savings ranging from 40% to 55% based on agitating only the feed, not the entire tank.

Plant loading – Reduction of 70–80% in live load – proportional to retention time savings shown above.

Overall plant size – Reduction of up to 50% due to reduced unit size.

In addition to these major benefits, the small unit size also reduces shipping and installation costs as well as plant maintenance.

As this technology progresses, it provides process engineers with a unique tool for circuit design. It is becoming increasingly more important to demonstrate payback as the traditional approach of simply adding additional capacity is not as clear cut when determining payback with respect to complete utilization of the resource. As a result, it is becoming more important for mining companies to challenge traditional methods by evaluating innovative technology that can maximize the recovery of valuable minerals while substantially reducing capital and operating costs.

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