

# STACKCELL™ FLOTATION - A NEW TECHNOLOGY FOR FINE COAL RECOVERY

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## ABSTRACT

During the past decade, column flotation cells have become widely accepted for the upgrading of fine coal streams. This popularity can be largely attributed to the ability of columns to remove high-ash clays from the froth product via the addition of wash water to a relatively deep froth. While there are numerous successful column installations, discussions with both end-users and engineering firms have identified certain design criteria that can make these installations challenging. The greatest of these challenges is the overall size of the cells and the associated foundation loads. To address this problem, a new high-intensity flotation system known as the StackCell™ has been developed. This technology makes use of pre-aeration coupled with a high-shear feed canister. This arrangement provides efficient bubble-particle contacting, thereby substantially shortening the residence time required for coal collection and virtually eliminating most of the column height. This article reviews the design features of this innovative technology and presents recent data obtained from full-scale installations.

## INTRODUCTION

Column flotation has become the dominant method of recovering the fine fractions in the coal industry. The use of columns has led to increased metallurgical performance when compared to that of mechanical flotation cells. This improvement in product quality has been proven by comparing in plant flotation data to a release analysis curve (Dell et al., 1972). Studies have also been performed that show how the use of column flotation affects the bottom-line of a plant (Luttrell et al., 1999; Kohmuench et al., 2004; Baumgarth et al., 2005). These studies report that the plants benefit from an increase in overall yield due to the improvement in the product grade from the flotation circuit. This increase in product grade is linked to the application of wash water used in column flotation. This countercurrent flow of water is applied to the froth and minimizes the nonselective recovery of high-ash ultrafine material that is normally hydraulically entrained in the froth of conventional flotation machines.

Column flotation does have its own set of design challenges though. The first of these challenges is simply the size of the column. The cell must be tall in order to achieve the desired residence time and minimize internal mixing which can be detrimental to cell performance. This design minimizes the plant floor space required for the cell, but increases the foundation loads. The large size of the column also leads to difficulties with fabrication and installation of column cells. The economics associated with plant design typically lean toward fewer, large-diameter cells. The largest diameter cell that can be shipped in the United States as a single piece is 4.5 m (15 ft). Larger cells can be installed, but these cells must be shipped in multiple sections and require more on-site assembly. Additionally, larger diameter cells must be taller to maintain the proper aspect ratio, at least 2:1, which then adds to the overall foundation load.

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The design challenges mentioned above show that there is a need for a new generation of flotation machine. A machine that is capable of delivering column-like performance, while also improving upon some of the design and operational challenges associated with column flotation. Based on experience gained over the last decade with the design, engineering, and operation of coal flotation circuits, Eriez has developed a new flotation cell that offers high capacity, reduction in both size and horsepower and superior metallurgical performance. While column flotation will still be a requirement for some applications, this new approach offers an alternative that provides column-like performance with reduced capital, installation and operating costs.

## TECHNOLOGY DESCRIPTION

Figure 1 illustrates the working features of the StackCell™ technology. During operation, feed slurry is introduced to the cell through a side (or bottom) feed port. At this point, low pressure air is added to the feed slurry. The aerated feed slurry then travels into the aeration chamber where significant shear is imparted to the system. The shear forces imparted to the system are used to create bubbles for bubble-particle collisions. In fact, all of these bubble-particle collisions occur in the aeration chamber prior to discharge into the outer tank. Once the slurry enters the outer tank, phase separation occurs between the froth and pulp. A pulp level is maintained in the outer tank to provide a deep froth that can be washed to minimize the entrainment of ultrafine high-ash clay material. The froth overflows into a froth collection launder, while the tailings are discharged using either a control valve or mechanical weir system. The system is specifically designed to have both a small footprint and a gravity-driven feed system. This allows multiple units to be “stacked” in series on subsequent levels in the plant or placed ahead of existing column or convention flotation circuits.

### WHY MULTISTAGE?

The enhanced performance made possible by the “stacked” arrangement can be mathematically quantified using the standard tanks-in-series flotation model (Lynch et al., 1981). According to this model, the recovery (R) of a given species from a single well-mixed flotation tank can be estimated using:



**FIGURE 1**  
Schematic of the Eriez StackCell™

$$R = \frac{k\tau}{1 + k\tau} \quad [1]$$

in which  $k$  is the rate constant and  $\tau$  is the residence time. The flotation rate constant ( $k$ ) represents how quickly particles float and is normally reported in units of  $\text{min}^{-1}$  (i.e., mass floated per unit mass in the cell per unit time). This parameter is largely dependent on the coal properties, chemical types/dosages, aeration rate and the design and operation of the bubbleparticle contacting system. The residence (or retention) time, which is usually reported in minutes, represents the average amount of time that particles stay within the flotation pulp. As a rule-of-thumb, a mean residence time of about 4 minutes or so is typically required in

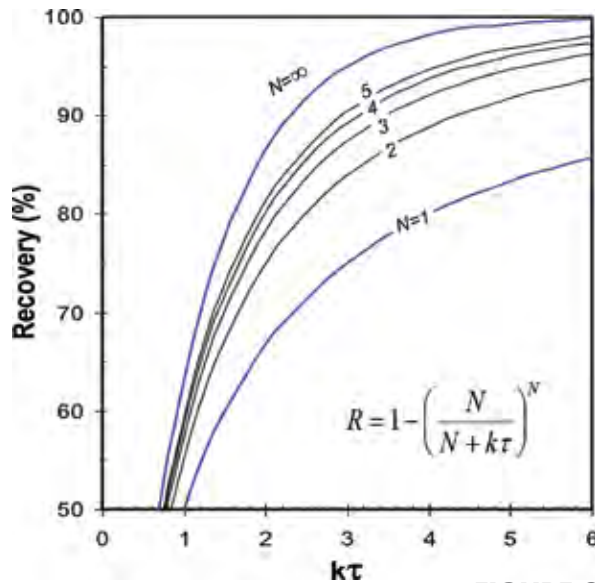
conventional flotation machines to achieve good recoveries of bituminous coals. The required residence time may be even longer for difficult-to-float coals that are very fine or oxidized.

According to Eq. (1), a 90% recovery would require a relatively large  $k\tau$  value of 9 (i.e.,  $9/(1+9) = 90\%$ ). One effective method of reducing the  $k\tau$  requirement is to arrange the flotation cells in series to reduce potential losses of floatable particles to the reject stream. In this case, the total recovery ( $R_N$ ) for a bank of  $N$  tanks in series can be determined from the arithmetic series given by:

$$R_N = R_i + R_i(1 - R_i) + R_i(1 - R_i)^2 + R_i(1 - R_i)^3 + \dots + R_i(1 - R_i)^{N-1} = 1 - (1 - R_i)^N \quad [2]$$

where  $R_i$  is the fraction recovery defined at  $\tau_i = \tau/N$ . Combining Eqs. (1) and (2) gives:

$$R_N = 1 - \left[ \frac{N}{N + k\tau} \right]^N \quad [3]$$



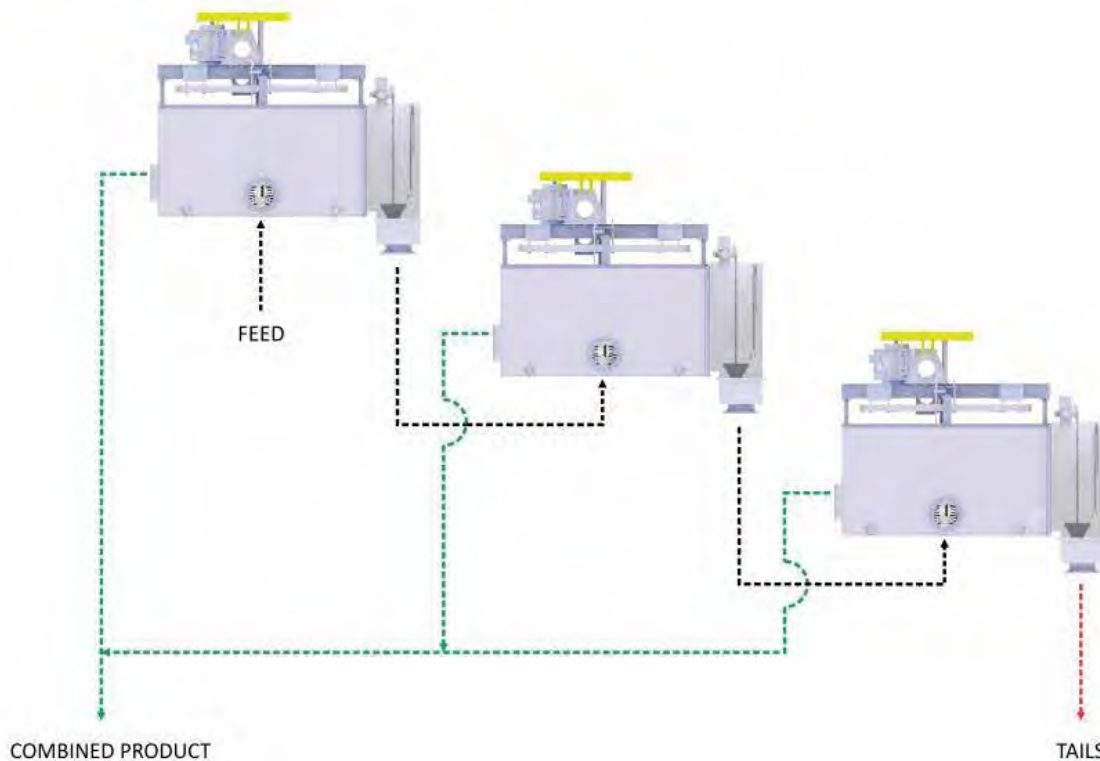
**FIGURE 2**

Effect of residence time and number of cells in series on the recovery of floatable material (assumes  $k = 0.8 \text{ min}^{-1}$ )

This expression is plotted in Figure 2 as a function of residence time for different numbers of cells ( $N$ ) in series and an assumed rate constant of  $0.8 \text{ min}^{-1}$ . Based on these estimates, a single cell would achieve a recovery of only 76.2% after 4 minutes of residence time. For the same total 4 minutes of residence time, the recovery would increase to 85.2% after two cells, 88.7% after three cells, 90.5% after four cells and 91.6% after five cells. As such, this analysis suggests that three to four cells in series provides a good balance since additional cells provide little incremental improvement in recovery compared to the increased cost of purchasing more cells.

Previous studies by Stanley et al. (2006) demonstrated the advantages of cell-to-cell circuitry for full-scale column flotation plants. Unfortunately, cell-to-cell circuitry is difficult to apply for columns due to their

tall aspect ratio and large volumetric footprint. On the other hand, the modular design of the StackCell™ easily accommodates the in-series configuration to take advantage of improved mixing conditions. Therefore, as shown in Figure 3, the preferred arrangement of the StackCell™ technology is three to four sequential stages for new installations. The technology can also be employed as a retrofit scalping unit placed ahead (or behind) existing column cells or mechanical flotation machines for additional capacity in the flotation circuit.



**FIGURE 3**

Preferred layout of StackCell™ flotation modules

## WHY INTENSE AGITATION?

Another unique feature of the StackCell™ technology is the use of a high-shear, bubble-particle contactor in place of the conventional rotor-stator mechanism historically used by mechanical flotation cells. Instead of operating with a large volume tank, the StackCell™ forces the bubbles and particles to contact within a very small confined area within an aeration chamber. Under this highly turbulent environment, the flotation rate constant ( $k$ ) can be expressed as:

$$k \propto C_b C_p E \quad [4]$$

in which  $C_b$  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 high-shear environment within the aeration chamber provides an energy dissipation level that is substantially higher than that produced by conventional flotation machines, thereby enhancing the recovery of difficult-to-float particles. 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 (Kohmuench et al., 2008). This allows the input energy to be used for gas dispersion and contacting and not for particle suspension. Moreover, the intense mixing shears the low-pressure air blown into the machine into extremely small bubbles, which substantially increases the concentration of bubbles present in the contacting chamber. This approach ensures that the maximum concentration of floatable particles and gas bubbles are present during the high-shear contacting.

According to Eq. (1), the very high rate constant ( $k$ ) created by the high-shear environment within the aeration chamber allows the StackCell™ to operate at a correspondingly lower residence time ( $\tau$ ) without adversely impacting the recovery. Field studies conducted with a pilot-scale unit showed that a residence time of less than 10 seconds was often adequate for good contacting when using the StackCell™ technology. Consequently, the required cell volume for a StackCell™ installation is significantly less, thereby reducing both equipment and installation costs. Structural steel requirements are considerably less due to the reduction in tank weight and live load. For a typical installation, the overall space requirement for the stacked-cell design is half the volume of an equivalent column circuit. Shipping and installation are also simplified since the units can be shipped fully assembled and lifted into place, complete and without field welding. Moreover, the energy input per unit ton processed is typically lower for the StackCell™ since energy is only expended for the purpose of creating bubbles and for bubble-particle contacting, and not for particle suspension like conventional flotation cells. In addition, the aeration chamber operates under a near-atmospheric pressure in a manner that removes the need for a compressor to overcome the hydrostatic or dynamic head. As a result, a low-pressure and maintenance-friendly blower can be used as opposed to a compressor.

## WHY FROTH WASHING?

Much like column flotation, the StackCell™ technology makes use of a froth washing system to avoid the hydraulic carryover of ultrafine high-ash slimes into the froth product (Kohmuench et al., 2004). In the case of the StackCell™, an overhead drip pan wash water distributor is utilized to reduce plugging problems that are often associated with submerged wash water distributors (see Figure 4). The drip pan design also provides excellent coverage of the entire surface area of the cell, and is easier for plant workers to maintain. For best performance, sufficient wash water must be added to fully displace the water carried by the froth into the clean coal launder. This requirement is normally reported as the number of dilution washes (i.e., wash water flow rate divided by the froth water flow rate). Normally, 1.1 to 1.3 dilution washes are required for good performance in coal applications. Despite the low-profile, the StackCell™ is designed so that a relatively deep froth (45-75 cm) can be maintained to maximize the froth washing action. Also, limitations associated with froth overloading that frequently occurs with column type cells is greatly reduced with the StackCell™ system due to the greater surface area resulting from the use of multiple cells.

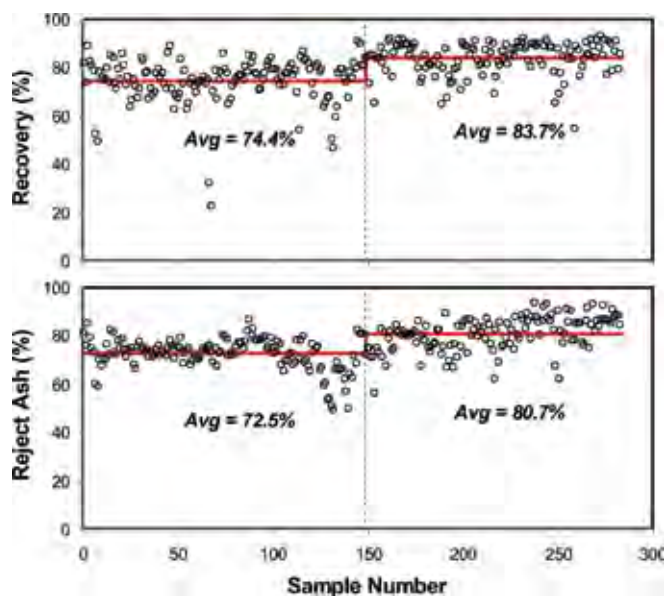


**FIGURE 4**  
Drip pan used for wash water distribution

## INDUSTRIAL EVALUATION

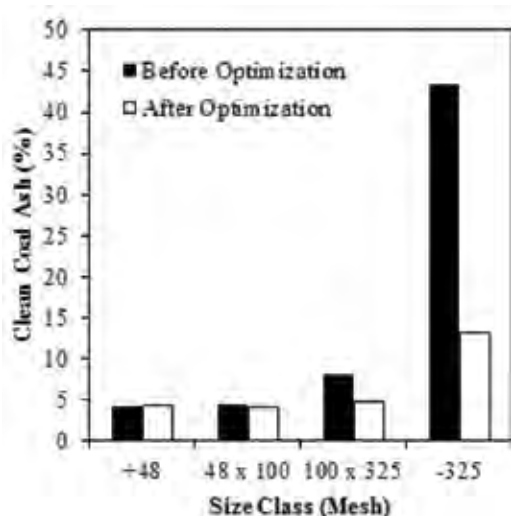
In order to demonstrate the performance capabilities of the StackCell™ technology, a full-scale unit was installed and commissioned at an industrial coal preparation plant. The plant processed run-of-mine coals from several seams supplied by both underground and surface mines. The StackCell™ unit consisted of a single 3.7-m (12-ft) diameter cell equipped with a 76-cm (30-inch) diameter aeration chamber. The single StackCell™ unit 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.

Figure 5 shows the impact of the StackCell™ installation on the combustible recovery and refuse ash for the entire flotation circuit. For the first 149 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 only about 5-10 seconds to the total flotation circuit. More recently, the average monthly plant recoveries have increased to more than 90% (i.e., 90.88%), while the average monthly tailings ash values have increased to nearly 86% (i.e., 85.9%).



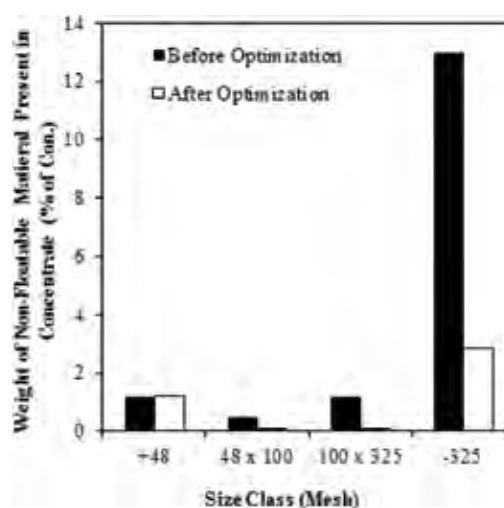
**FIGURE 5**  
Change in flotation circuit performance due to the installation of the StackCell™ technology (dashed line represents the sample where the changeover occurred)

Close inspection of the test data indicates a gradual improvement in overall performance since the StackCell™ was installed. The continued improvement can be largely attributed to the optimization of operating variables such as reagent dosage, froth depth, aeration rate and wash water addition rate that occurred over time as a result of fine tuning by the plant operators. For example, Figures 6 and 7 show the impact of the optimization on the clean coal quality and recovery. The high ash content in the minus 325 mesh fraction was substantially reduced from about 43.4% to less than 13.3% once the froth washing system was optimized. This is due to the elimination of entrained ultrafine non-floatable high ash material in the minus 325 mesh fraction. Before the optimization of the wash water addition, roughly 13% of the concentrate was made up of this entrained material. After the wash water was optimized roughly 2.84% of the concentrate was made up of this high ash material. The plant data continues to show that the quality of the froth product is sensitive to froth depth and wash water addition rate. Therefore, it is important that these values be properly monitored and controlled to optimum settings.



**FIGURE 6**

Effect of wash water optimization on StackCell™ size-by-size clean coal ash



**FIGURE 7**

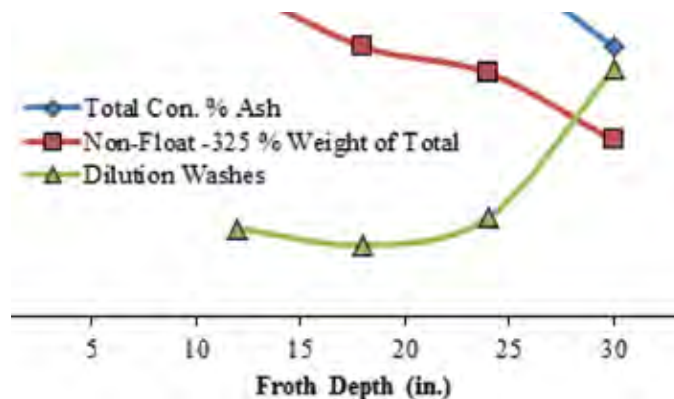
Effect of wash water on the size-by-size amount of non-floatable material present in the concentrate

In light of the importance of froth depth and wash water addition rate, several series of parametric tests were also conducted to demonstrate how the StackCell™ would react to changes in these important variables. The plant's normal operating point was used as the baseline for the parameter sweep. The cell was swept through a total of four operating points for each variable, while the other variables were held constant at their normal operating condition. The test matrix is summarized in Table 1.

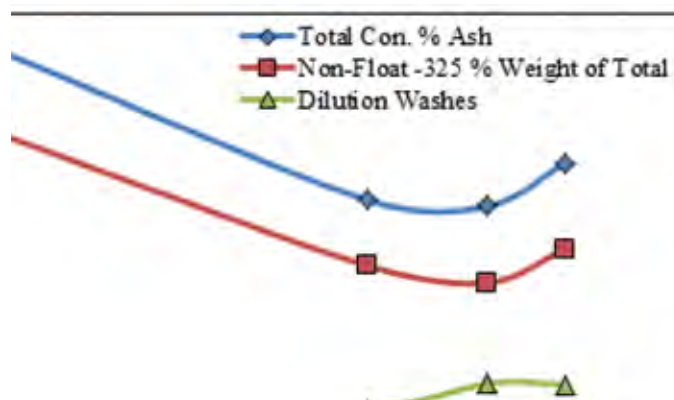
Test ID	Froth Level cm (inch)	Wash Water Rate m <sup>3</sup> /hr (GPM)
A	76 (30)	82 (360)
B	61 (24)	82 (360)
C	46 (18)	82 (360)
D	30 (12)	82 (360)
E	61 (24)	82 (360)
F	61 (24)	0
G	61 (24)	59 (260)
H	61 (24)	78 (345)
I	61 (24)	91 (400)

**TABLE 1**

Test matrix used for StackCell™ testing



**FIGURE 8**  
Concentrate quality and dilution wash data for various froth depths



**FIGURE 9**  
Concentrate quality and dilution wash data for various wash water addition rates

Figure 8 shows how the cell performed with respect to a change in froth depth. Increasing the froth depth lead to an improved concentrate ash and reduced the amount of non-floatable material present in the concentrate. The minimum froth depth tested of 30 cm (12 inches) produced the highest concentrate ash of 8.37% and contained the largest amount of minus 325 mesh hydrophilic material (6.61% of the total concentrate weight). As froth depth increased the flotation process became more selective. At a more acceptable froth depth of 60 cm (24 inches), a better concentrate ash of 7.12% was produced, while the minus 325 mesh hydrophilic material in this sample only made up 4.88% of the total concentrate weight. As expected, the deepest froth depth tested of 76 cm (30 inches) produced the best results with respect to concentrate ash and hydrophilic material present in the concentrate. This deep froth resulted in a concentrate ash of 5.42% and the minus 325 mesh hydrophilic material comprised only 3.53% of the total concentrate weight. The spike seen in the dilution washes data is likely linked to the drop in total weight recovery caused by the improved ash rejection. When a smaller amount of high percent solids product is being produced, less water reports to the concentrate and the effective number of dilution washes increases.

Figure 9 shows how the StackCell™ performance changes with varying wash water rates. As with the previous set of data, the cell follows the expected trend with respect to total concentrate ash, i.e., ash content decreased as the amount of wash water increased. Overall, the concentrate ash was a maximum of 11.0% when no wash water was added to the cell. The weight of undesirable minus 325 mesh hydrophilic material present in the concentrate was also highest at 8.7% when no wash water was added. The minimum ash value occurred with the addition of 345 GPM of wash water, resulting in a 6.7% concentrate ash. The 260 GPM test also produced a very similar, albeit slightly higher, concentrate ash of 6.9%.

The concentrate samples from the three non-zero rates tested were made up of similar amounts of minus 325 mesh hydrophilic material ranging from 4.7% to 5.6% of the total concentrate weight at the 345 GPM and the 400 GPM tests respectively. Interestingly, the ash content of the concentrate increased slightly at the highest wash water rate. One possibility for the higher value was that pressure variations due to pump cycling/surging in the preparation plant created fluctuations in the wash water flow rate. While this could be a contributing factor to the high ash value, it is unlikely that it is solely responsible since the other data points were subjected to the same testing conditions. A more likely explanation for the unexpected increase in ash is short-circuiting of the wash water into the concentrate. This possibility is supported by the fact that the dilution washes also did not increase as the water rate was increased to the highest rate. Thus, more of the wash water must have reported to the concentrate, which reduced the dilution washes for that test. Further testing is suggested in order to determine whether this phenomenon is site specific or an inherent characteristic of this particular flotation machine.

## SUMMARY

A new high-capacity flotation technology, called the StackCell™, has been developed as an alternative to both conventional and column flotation machines. This technology makes use of pre-aeration, and a high-shear aeration chamber that provides efficient bubble-particle contacting, thereby substantially shortening the residence time required for coal flotation. Other potential advantages of the process include low air pressure requirements, low capital and installation costs, and increased flexibility in plant retrofit applications. Recent full-scale plant trials suggest that the technology can provide product qualities comparable to column flotation systems using a low profile design. Further testing shows that the StackCell™ follows the expected trends with respect to concentrate ash when it experiences changes in froth depth and wash water addition rate. While it is not expected that this new technology will replace the need for column flotation, it does provide an alternate means to efficiently achieve column-like performance when plant space and/or capital is limited. In particular, the small size and low weight of this new technology makes it amenable to low-cost plant upgrades where a single unit can be placed into a currently overloaded flotation circuit with minimal retrofit costs.



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