Applications of the HydroFloat Air-Assisted Gravity Separator

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ABSTRACT

Froth flotation is widely considered the most cost effective and versatile process for the separation of fine particles. Both column and conventional flotation have been successfully applied for the recovery of particles ranging from 30 mesh to sub-micron sizes. Unfortunately, the commercial application of flotation to recover coarser particles is not practical due to limits associated with bubble-particle buoyancy and detachment. These limits have been overcome through the development of an innovative air-assisted gravity separator known as the HydroFloat. The HydroFloat combines the versatility and selectivity of a flotation process with the low cost and high capacity of a gravity concentration process. This paper presents a review of the theoretical basis for this novel technology as well as data from phosphate, potash, feldspar, and other industrial mineral applications.

INTRODUCTION

Hindered-bed separators are commonly used in the minerals industry for particle classification. These units can also be employed for mineral concentration provided that the particle size range and density differences are within acceptable limits. However, these separators often suffer from the misplacement of low-density coarse particles to the high-density underflow. This shortcoming is due to the accumulation of coarse low-density particles that gather at the top of the teeter bed. These particles are too light to penetrate the teeter bed, but are too heavy to be carried by the rising water into the overflow launder. These particles are eventually forced by mass action downward to the discharge as more particles accumulate at the top of the teeter bed. This inherent inefficiency can be partially corrected by increasing the teeter-water velocity to convey the coarse, low-density solids to the overflow. Unfortunately, the higher water rates will cause fine, high-density solids to be misplaced to the overflow launder, thereby reducing the separation efficiency.

To overcome the shortcomings of traditional hindered-bed separators, a novel device known as the HydroFloat separator was developed. As shown in Figure 1, the HydroFloat unit consists of a rectangular tank subdivided into an upper separation chamber and a lower dewatering cone. The device operates much like a traditional hindered-bed separator with the feed settling against an upward current of fluidization water. The fluidization (teeter) water is supplied through a network of pipes that extend across the bottom of the entire cross-sectional area of the separation chamber. However, in the case of the HydroFloat separator, the teeter bed is continuously aerated by injecting compressed air and a small amount of frothing agent into the fluidization water. The gas is dispersed into small air bubbles by circulating the water through a high-shear mixer in a closed-loop configuration with a centrifugal pump.

The air bubbles become attached to the hydrophobic particles within the teeter bed, thereby reducing their effective density. The particles may be naturally hydrophobic or made hydrophobic through the addition of flotation collectors. The lighter bubble-particle aggregates rise to the top of the denser teeter bed and overflow the top of the separation chamber. Unlike flotation, the bubble-particle agglomerates do not need to have sufficient buoyancy to rise to the top of the cell. Instead, the teetering effect of the hindered bed forces the low-density agglomerates to overflow into the product launder. Hydrophilic particles that do not attach to the air bubbles continue to move down through the teeter bed and eventually settle into the dewatering cone. These particles are discharged as a high solids stream (e.g., 75% solids) through a control valve at the bottom of the separator. The valve is actuated in response to a control signal provided by a pressure transducer mounted to the side of the separation chamber. This configuration allows a constant effective density to be maintained within the teeter bed.

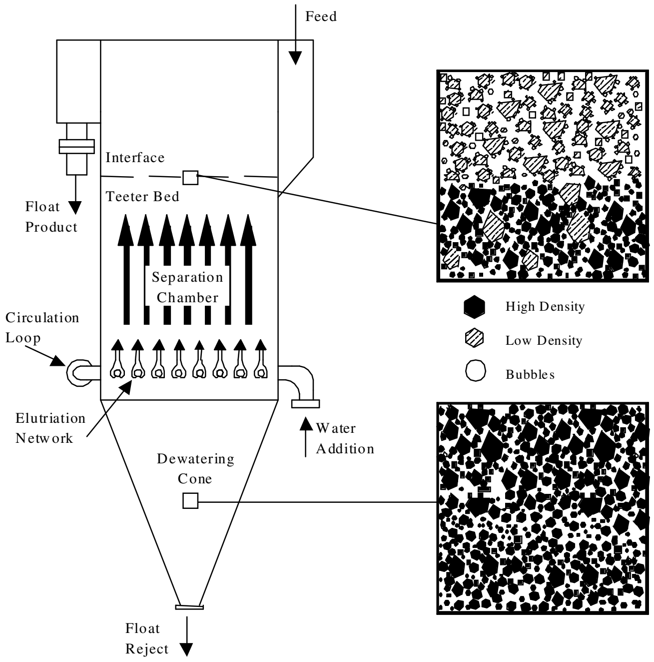

Figure 1. Schematic Diagram of the HydroFloat Separator.

The HydroFloat separator can be theoretically applied to any system where differences in apparent density can be created by the selective attachment of air bubbles. Although not a requirement, the preferred mode of operation would be to make the low-density component hydrophobic so that the greatest difference in specific gravity would be achieved. Compared to traditional froth flotation processes, the HydroFloat separator offers several important advantages for treating coarse material.

These include enhanced bubble-particle contacting, better control of particle residence time, lower axial mixing/cell turbulence, and reduced air consumption.

PROCESS THEORY

The reaction, or flotation, rate for a process is indicative of the speed at which the separation will proceed. In mineral flotation the reaction rate is controlled by several probabilities; e.g., collision, adhesion and detachment. The attachment of particles to air bubbles is the underlying principle upon which all flotation processes are based. This phenomenon takes place via bubble-particle collision followed by the selective attachment of hydrophobic particles to the bubble surface. Particles may detach if the resultant bubble-particle aggregate is thermodynamically unstable. According to Sutherland (1948), the attachment process may be described by a series of mathematical probabilities given by:

$$P = P_c P_a (1 - P_d) \qquad \text{(EQ 1)}$$

in which P_c is the probability of collision, P_a the probability of adhesion, and P_d the probability of detachment. The attachment and detachment probabilities are controlled by the process surface chemistry and cell hydrodynamics, respectively. In an open (free settling) system, the collision probability is quite low due to the low particle concentration. However, at higher concentrations, the crowding effect within the hindered bed increases the probability of collision. This phenomenon is due to the compression of the fluid streamlines around the bubbles as they rise through the teeter bed. The increased probability of collision can result in reaction rates that are several orders of magnitude higher than found in conventional flotation.

Hindered-bed separators also operate as low-turbulence devices. As a result, particle detachment is minimized due to a reduction in localized turbulence. Studies conducted by Woodburn, *et al*., (1971) suggest:

$$P_d = (D_p / D_p *)^x \qquad \text{(EQ 2)}$$

in which D_p is the particle diameter to be floated, D_p* is the maximum floatable particle diameter, and x is an experimental constant (typically 3/2). Factors that influence the magnitude of D_p* include pulp chemistry (surface tension and contact angle), physical particle properties (size, density, composition, and shape), and cell agitation intensity. Theoretical D_p* values have been calculated by Schulze (1984) from the tensile and shear stresses acting on bubble-particle aggregates under homogenous turbulence. The degree of turbulence was quantified in terms of the induced root mean square velocity (*RMSV*). According to this theoretical study, the maximum size of particles that may be recovered by flotation increases by more than an order of magnitude when changing from high to low turbulence. According to Barbery (1984), the optimum conditions for coarse particle flotation occur when cell agitation intensity is reduced to a point just sufficient to maintain the particles in suspension. Thus, a teeter bed is an ideal environment for minimizing particle detachment.

The mixers-in-series model provides a convenient framework for analyzing this phenomenon (Arbiter and Harris, 1962; Bull, 1966). According to this model, the cumulative fractional recovery (*R*) of a given particle species can be determined using the expression:

$$R = 1 - (1 + k\tau_p)^{-n} \qquad \text{(EQ 3)}$$

in which *k* is the flotation rate constant, τ_p is the particle residence time, and *n* is the number of equivalent mixers. Figure 2 shows recovery determined from the above relationship for different values of *n* as a function of the dimensionless product $k\tau_p$. In most cases, *n* is assumed to be equal to the number of cells in the flotation bank. This assumption is generally valid for a cell-to-cell flotation bank. However, the magnitude of *n* is typically smaller for flow-through flotation banks that have a significant amount of intermixing. The appropriate value of *n* can be readily estimated for any cell configuration using residence time distribution (RTD) data that have been collected using solid or liquid tracers. Details related to this procedure have been described elsewhere (Mankosa *et al*., 1992).

The HydroFloat cell operates under nearly plug-flow conditions due to the low degree of axial mixing afforded by the uniform distribution of particles across the teeter bed. As a result, the cell operates as if it were comprised of a large number of cells in series (i.e., high value of *n*). As shown in Figure 2, this characteristic allows a single unit to achieve the same recovery as a multi-cell bank of conventional cells (all other conditions equal). In other words, the HydroFloat cell makes more effective use of the available cell volume than well-mixed conventional cells or open columns.

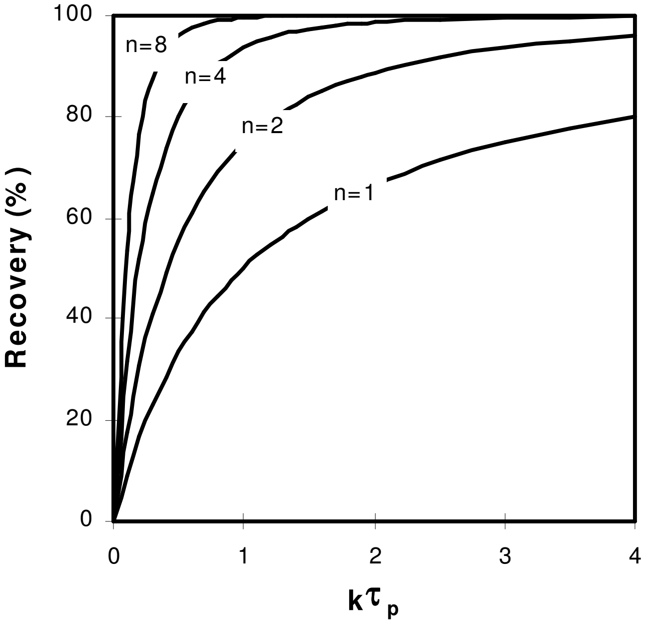

Figure 2. Theoretical Recovery as a Function of Flotation Rate and Retention Time.

The hindered-bed environment also influences particle retention time, and hence, particle recovery. In column flotation, particles settle vertically through the cell either with the fluid flow (co-current) or opposite to it (counter-current). A counter-current arrangement has obvious advantages since the settling velocity is reduced by the upward flow of liquid resulting in a higher retention time. Hindered settling, as previously explained, provides an environment in which the particles never achieve their terminal free-fall velocity. As a result, the effective particle velocity through the cell is greatly reduced, providing a significant increase in retention time as compared to a free-settling system. The longer retention time also allows good recoveries to be maintained without increasing cell volume.

APPLICATION TESTING

Phosphate

The United States is the world's largest producer of phosphate rock. In 1999, this industry accounted for approximately 45 million tons of marketable product valued at more than $1.1 billion annually (United States Geological Survey, Mineral Commodity Summaries, January 1999). Approximately 83% of this production can be attributed to mines located in Florida and North Carolina.

Prior to marketing, the run-of-mine phosphate matrix must be upgraded to separate the valuable phosphate grains from other impurities. The first stage of processing involves screening to recover a coarse (plus 14 mesh) high-grade pebble product. The screen underflow is subsequently deslimed at 150 mesh to remove fine clays. Although 20-30% of the phosphate contained in the matrix is present in the fine fraction, technologies currently do not exist that permit this material to be recovered in a cost-effective manner. The remaining 14 x 150 mesh fraction is classified into coarse (e.g., 14 x 35 mesh) and fine (e.g., 35 x 150 mesh) fractions that are upgraded using conventional flotation machines, column flotation cells, or other novel techniques such as belt flotation (Moudgil and Gupta, 1989). The fine fraction (35 x 150 mesh) generally responds well to froth flotation. In most cases, conventional (mechanical) flotation cells can be used to produce acceptable concentrate grades with recoveries in excess of 90%. On the other hand, high recoveries are often difficult to maintain for the coarser (14 x 35 mesh) fraction.

Prior work has shown that the recovery of coarse particles (e.g., >30 mesh) can be less than 50% in many industrial operations (Davis and Hood, 1992). For example, Figure 3 illustrates the sharp reduction in recovery as particle size increases from 0.1 mm (150 mesh) to 1 mm (16 mesh) for a Florida phosphate operation. In many cases, attempts by plant operators to improve coarse particle recovery often produce an undesirable side effect of diminishing flotation selectivity.

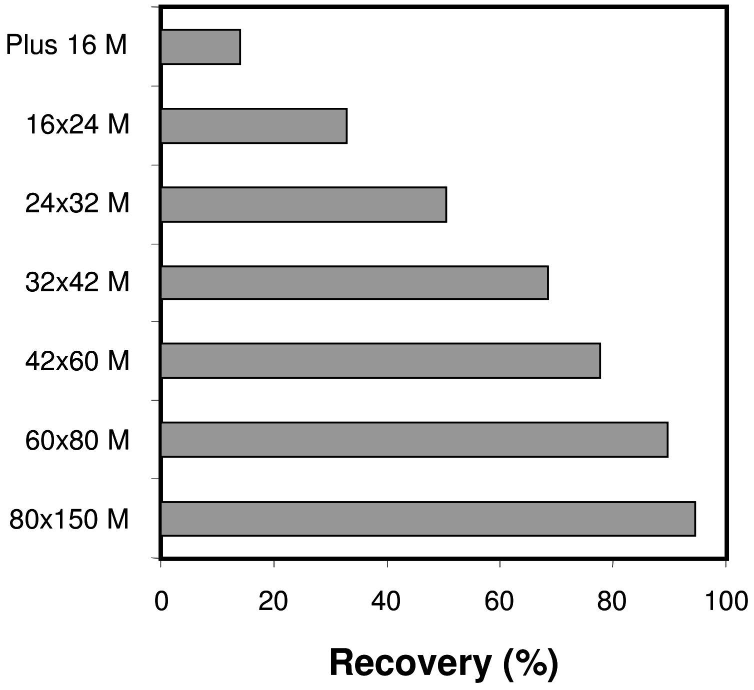

Figure 3. Size-by-Size Recovery for a Typical North American Phosphate Producer.

The United States Bureau of Mines (USBM) conducted one of the most comprehensive studies of the coarse particle recovery problem in the phosphate industry (Davis and Hood, 1993). This investigation involved the sampling of seven Florida phosphate operations to identify sources of phosphate losses that occur during beneficiation. According to this field survey, approximately 50 million tons of flotation tailings are discarded each year in the phosphate industry. Although the tailings contain only 4% of the matrix phosphate, more than half of the potentially recoverable phosphate in the tailings is concentrated in the plus 30 mesh fraction. In all seven plants, the coarse fraction was higher in grade than overall feed to the flotation circuits. In some cases, the grade of the plus 30 mesh fraction in the tailings approached 20% P_2O_5. The USBM study indicated that the flotation recovery of the plus 35 mesh fraction averaged only 60% for the seven sites included in the survey. Furthermore, the study concluded that of the seven phosphate operations, none have been successful in efficiently recovering the coarse phosphate particles.

Based on the established needs of the phosphate industry for a coarse particle recovery system, a pilot-scale test program was undertaken to evaluate the HydroFloat separator at a major phosphate plant in Florida. A schematic of the pilot-scale test circuit used for this study is shown in Figure 4. The test circuit consisted of three primary unit operations; i.e., pilot-scale classifier, slurry conditioner, and HydroFloat separator. In this circuit, the coarse underflow from an existing bank of classifying cyclones was fed to a 1.5x1.5 meter (5 ft x 5 ft) teeter-bed classifier (Eriez CrossFlow Separator). The underflow from the classifier was passed to the conditioning unit where appropriate reagents were added to control pH (ammonia) and particle hydrophobicity (fatty acid/fuel oil blend).

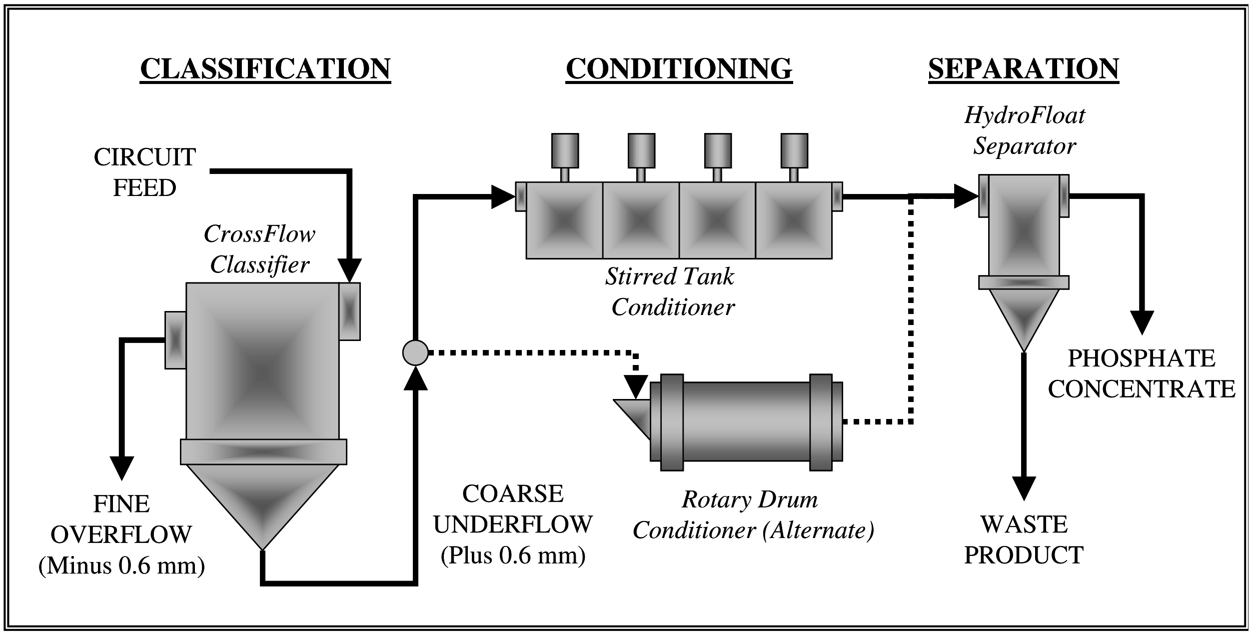

Figure 4. In-Plant Pilot-Scale Test Circuit.

The test circuit was configured so that feed conditioning could be performed using either a stirred-tank (four stage) or a single-stage rotary drum (76-cm/30-inch diameter) conditioner. The conditioner circuit was able to operate reliably at approximately 40-75% solids at a maximum mass flow rate of 4-6 tonne/hr (dry solids). The conditioned slurry flowed by gravity to the feed inlet for either the HydroFloat separator or a 50-cm (20-inch) diameter flotation column. This arrangement made it possible to directly compare the effectiveness of the HydroFloat separator with existing column technology. The test circuit was installed with all necessary components (i.e., reagent pumps, etc.) required to operate the separator in continuous mode at the desired capacity.

To compare the HydroFloat with current state-of-the-art column technology, comparison tests were conducted with an open-column flotation cell. The column utilized state-of-the-art sparger technology and was supplied with instrumentation to maintain level and monitor air and water flow rates. Comparison tests were conducted on each cell as a function of various operating conditions. The objective of the test program was to collect sufficient data using each separator and generate comparable product grade versus recovery curves.

The results from the column comparison tests are presented in Figures 5 and 6. The data shown in Figure 5 indicate that both the HydroFloat and open column operated on the same product grade versus recovery curve. The BPL recovery, however, was substantially higher for the HydroFloat system. The result is particularly impressive considering that the open column was operated at a substantially lower feed rate than the HydroFloat. As shown, the open column was able to achieve BPL recoveries exceeding 90% at a feed rate of 6.5 tph/m^2 (0.66 tph/ft^2). However, as the feed rate increased to a higher value of 9.8 tph/m^2 (1.0 tph/ft^2), the BPL recovery dropped significantly. The HydroFloat, on the other hand (Figure 6), was able to maintain a BPL recovery averaging 98% at a feed rate exceeding 19.6 tph/m^2 (2.0 tph/ft^2). It should be noted that at a feed rate of 24.5 tph/m^2 (2.5 tph/ft^2), the capacity of the conditioner (not the HydroFloat) was exceeded. At this capacity, poor conditioning caused a decrease in the downstream performance of the HydroFloat separator. These results clearly demonstrate that the HydroFloat capacity exceeds that of flotation column cells currently used by the phosphate industry.

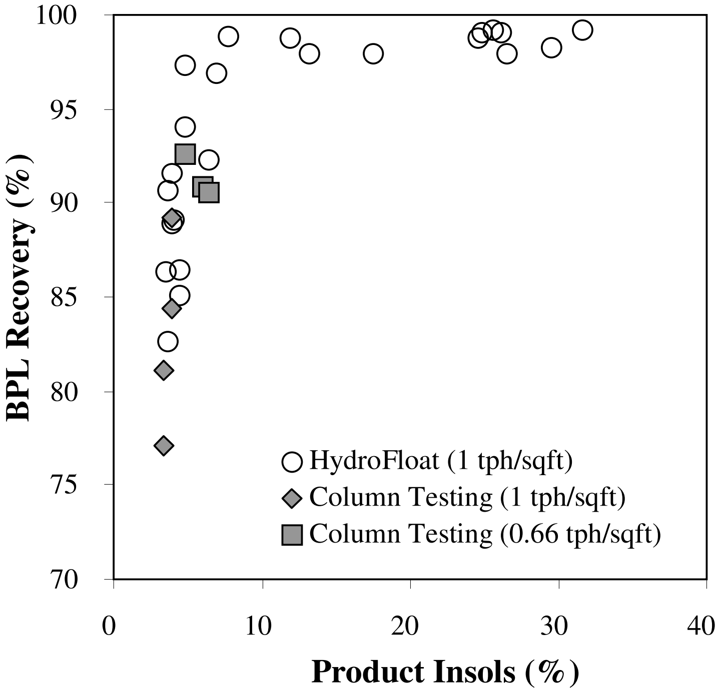

Figure 5. BPL Recovery Comparison for the Column and HydroFloat Separators.

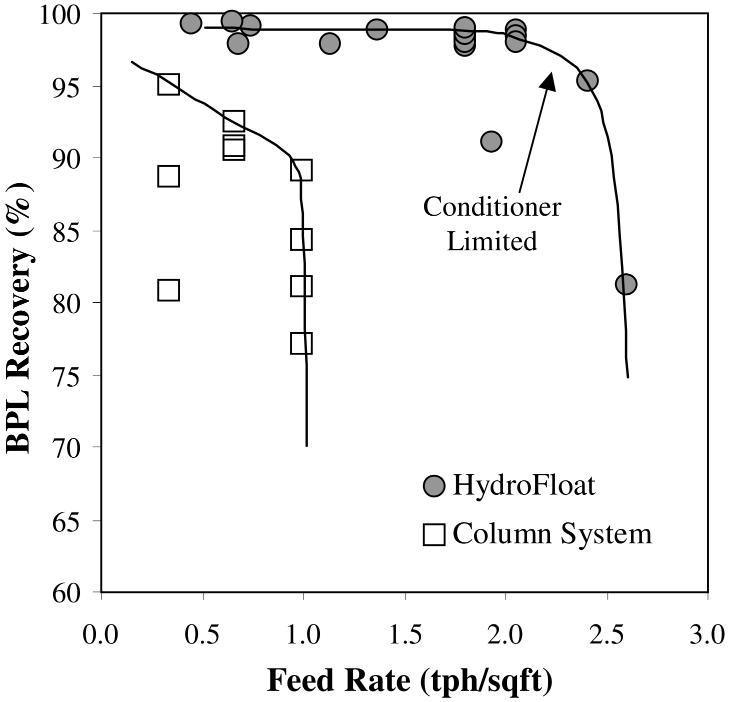

Figure 6. Feed Rate Comparison for the Column and HydroFloat Systems.

A summary of all of the test data obtained during this evaluation is provided in Figure 7. The improved flotation response for the drum conditioner, which was demonstrated in an earlier laboratory evaluation, was also verified through the pilot-scale testing. As shown, the rotary conditioner improved BPL recovery by approximately 20 percentage points. In fact, the BPL recovery approached 98% at a product insols grade between 5% and 12%. The high concentrate grade is due to the improved recovery of the coarse, high-grade particles normally lost in traditional mechanical flotation. When using the HydroFloat system, over 80% of the coarsest phosphate particles (+10 mesh) were recovered. Figure 8 shows the typical size-by-size BPL recoveries and insols rejections obtained using the HydroFloat separator. As shown, the HydroFloat was able to maintain a high BPL recovery and insols rejection for all size classes.

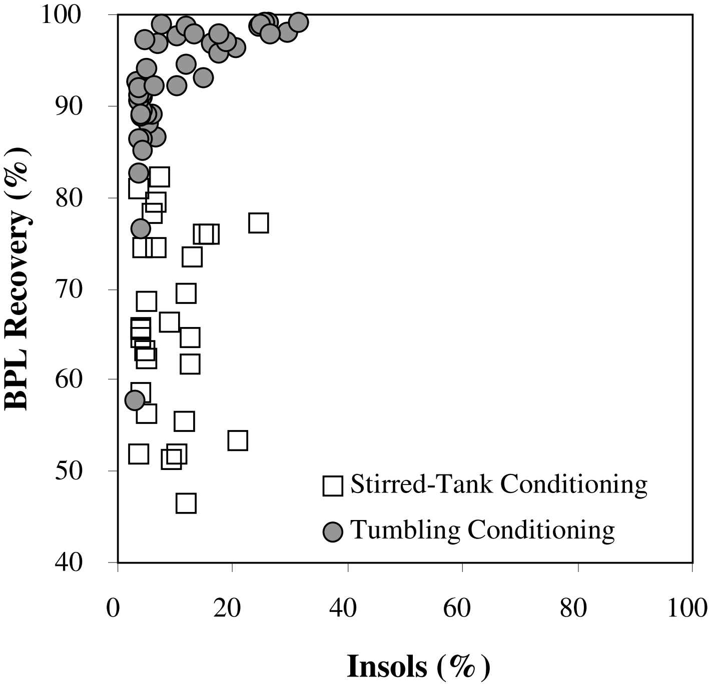

Figure 7. Overall BPL Recovery versus Product Insols Curve.

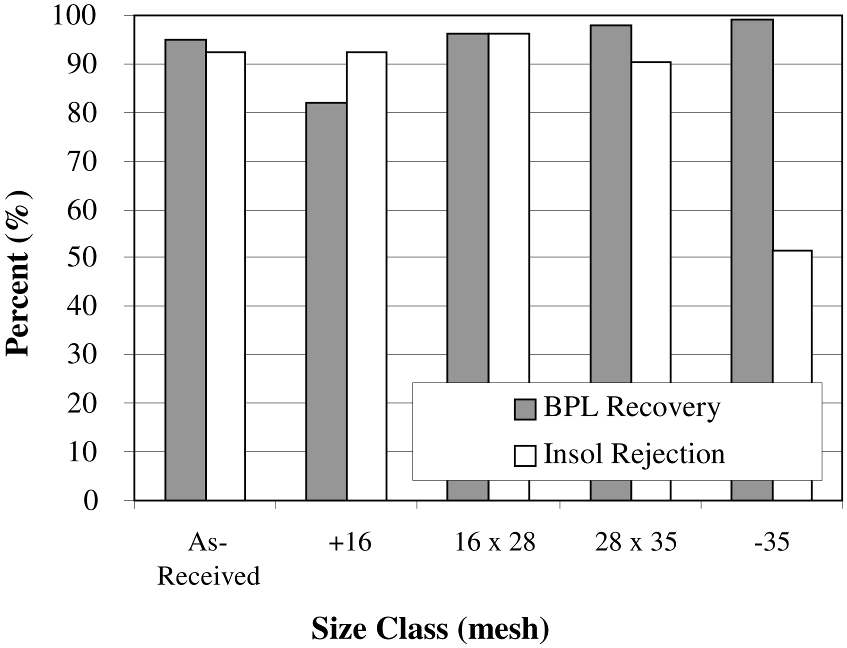

Figure 8. Typical Size-by-Size Recovery for In-Plant HydroFloat Evaluation.

Potash

An important commodity for the manufacture of fertilizer, potash occurs as sylvinite ores that contain sylvite (KCl), halite (NaCl), and insolubles. Flotation of the sylvite is achieved using a cationic collector. Flotation is carried out in saturated brine using standard conventional flotation machines. Much like phosphate, potash is also recovered at a coarse particle size. The coarse concentrate commands a premium price and eliminates the need for granulation and compaction (Soto, 1993). With a top size of approximately 5 mesh, however, recovery of the coarse material is often low in comparison to the fine fraction (i.e., <1 mm). In an attempt to improve coarse particle recovery, an in-plant evaluation of the HydroFloat was conducted at PCS Potash in Saskatchewan, Canada.

Tests were conducted on a tailings stream from existing rougher flotation cells. This coarse reject fraction (mean size = 2.2 mm) contains approximately 8% K_2O and is currently being upgraded in a bank of conventional scavenger cells. Conditioning of the ore is completed at high percent solids (+75%) using an amine collector. A sample of this material was fed continuously to a 30-cm (12-inch) diameter, pilot-scale HydroFloat separator. Process brine was used as the fluidizing medium.

Tests were conducted as a function of air and elutriation rate in order to produce a grade versus recovery curve for the potash ore. For each test, samples of the product, reject, and feed streams were collected for assay. The solids feed rate to the HydroFloat was maintained at 15.7 tph/m^2 (1.6 tph/ft^2) and was delivered at 70% solids. For comparison, samples were also collected from the existing conventional cells that were operating in parallel to the HydroFloat.

The results from the in-plant tests are shown in Figures 9 and 10 as K_2O and mass recovery versus product grade. As shown, the average recovery of K_2O using the HydroFloat system is roughly double that which can be achieved by conventional flotation cells. The average K_2O recovery for the HydroFloat was 90.4% while the existing cells averaged 51.9% recovery. Unlike the HydroFloat, mechanical cells have a relatively short retention time, a high degree of turbulence (mixing), and a low probability of bubble/particle contacting due to the low percent solids content of the pulp. The obvious advantage of the high recovery offered by the HydroFloat system is the overall increase in mass yield or product tons. In fact, the average mass yield for the existing cells was 6.7%, while the HydroFloat achieved an average 13.9% weight recovery.

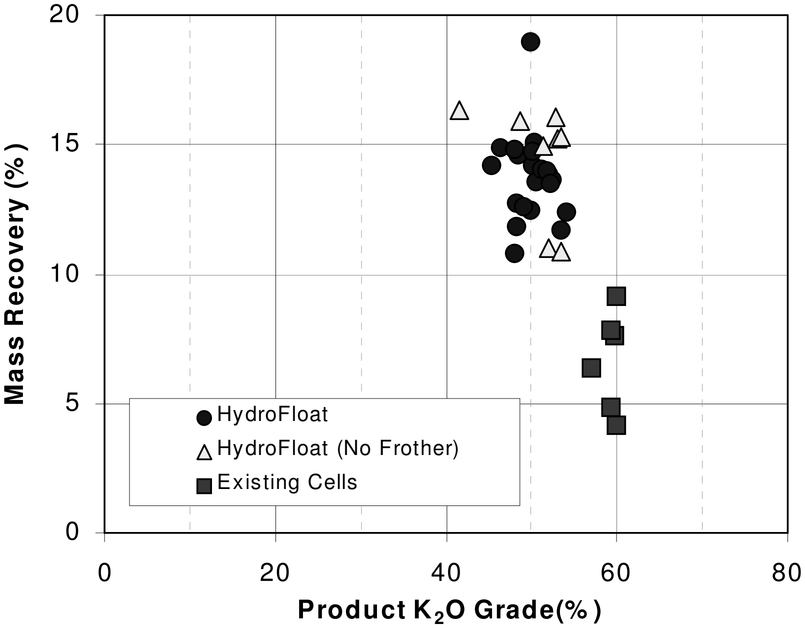

Figure 9. Mass Recovery verus Product Grade for HydroFloat In-Plant Testing of Potash.

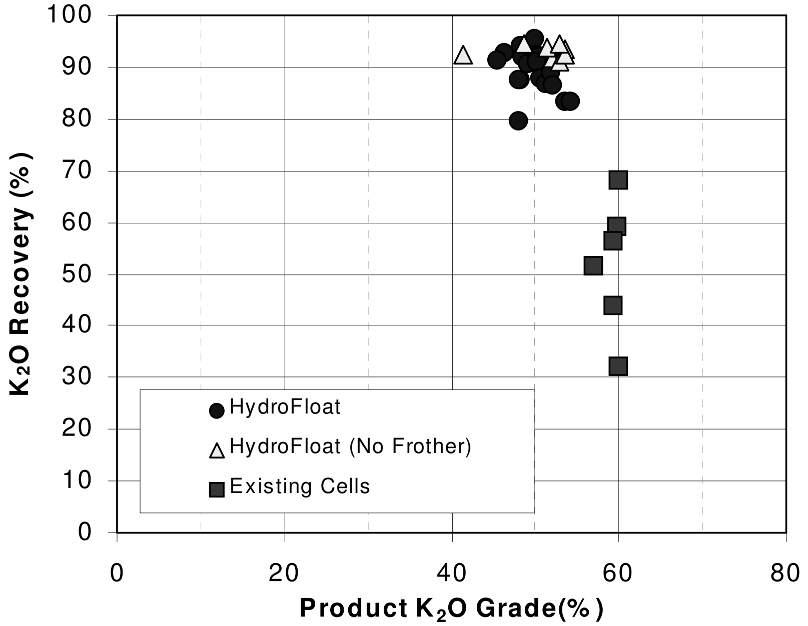

Figure 10. K_2O Recovery verus Product Grade for HydroFloat In-Plant Testing of Potash.

Feldspar

Feldspar is mined in several locations throughout the world and is used predominantly in the glass and ceramics industries. Difficulties are often observed with regard to coarse particle recovery via flotation. Consequently, feldspar ore is typically ground much finer than the liberation size in order to optimize plant flotation circuits. Mica and iron-bearing minerals are also found in the raw ore and are initially removed by flotation prior to the final separation of the high-grade feldspar particles from the silica gangue. Regardless, the successful recovery of coarse feldspar yields many advantages including the reduction of grinding costs and the subsequent decrease in fines production (i.e., over-grinding).

To evaluate the effectiveness of the HydroFloat for coarse feldspar recovery, a series of laboratory-scale tests were conducted on a bulk sample obtained from an existing producer. The starting sample was nominally 20x100 mesh and had a feldspar content of 25%. The predominant gangue mineral was quartz. The separation objective was to achieve a product containing 65% feldspar at a recovery of at least 85%. Tests were conducted as a function of feed rate (9.8-14.6 tph/m^2 or 1.0-1.5 tph/sqft) and collector addition. The process water was adjusted to a pH of 2.5 using sulfuric acid and conditioning was accomplished using a tumbling-type conditioner. Aeration rate was maintained at 0.3 m^3/min/m^2 (1 scfm/sqft). Samples of the feed, product, and reject streams were collected from each test for analysis.

The results from this series of tests are shown in Figure 11 as feldspar grade versus recovery. These findings indicate that the HydroFloat can recover 90% of the feldspar mineral at a concentrate grade greater than 65%.

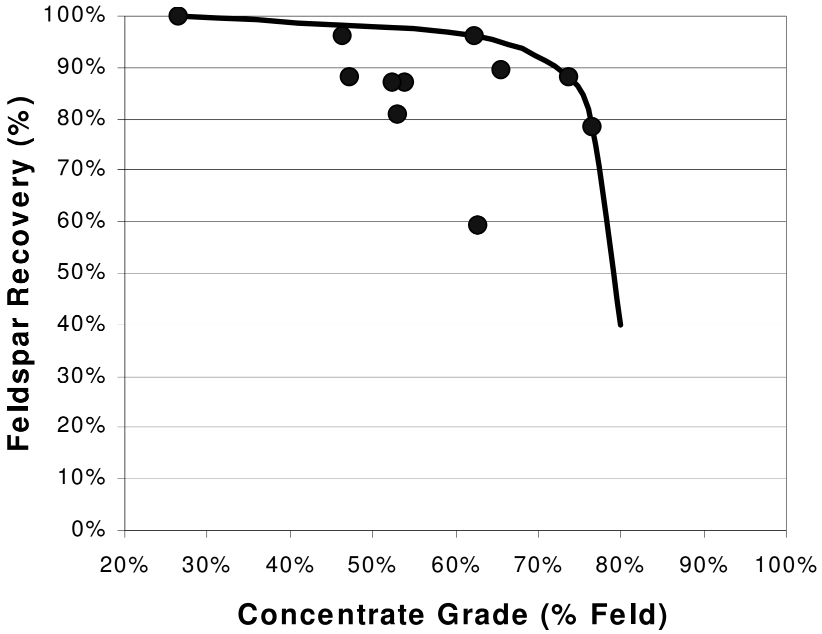

Figure 11. Feldspar Product Grade versus Recovery.

Coal

Gravity concentration is used almost exclusively in the coal industry for upgrading coal to achieve the desired market product specifications. In most applications, the run-of-mine coal is classified into three or more size fractions prior to separation. The smallest size fractions are typically 28x100 and –100 mesh. The –100 mesh fraction is treated using froth flotation while the 28x100 mesh material is usually concentrated with spirals. Spirals are flowing-film, gravity concentrators that effectively separate "sand size" material according to specific gravity.

More recently, teeter-bed separators are also being implemented for concentration of the 28x100 mesh fraction. Teeter-bed separators offer many advantages including less floor space, less head room, and automatic control. Additionally, teeter bed separators have a unit capacity up to 24.5 tph/m^2 (2.5 tph/sqft). This translates to 230 tph for a single 3x3 meter (10x10 ft) separator. By comparison, spirals have a unit capacity of 3-3.5 tph. Therefore, multiple spirals must be used to process typical plant tonnages. As a result, the performance of a spiral circuit must be quantified by averaging the efficiency of all the individual separators. In the previous example, this implies that 72 spirals must operate at the same process efficiency.

From a process efficiency point-of-view, the advantages of a single-unit operation are obvious. Unfortunately, teeter-bed separators can also suffer from process inefficiencies if oversize material is present. As described elsewhere (Reed *et al.*, 1995; Honaker, 1996), a teeter-bed separator classifies material based on the terminal hindered settling velocity. Fine and low-density particles report to the overflow while coarse and high-density material discharge through the underflow. As a result, misplaced coarse, low-density material will be lost with the tailings, resulting in a lower process efficiency.

The HydroFloat separator overcomes this problem through the addition of a small amount of air with the teeter water. In coal applications, the naturally hydrophobic particles adhere to the air bubbles reducing the effective density of the coarse particles. As a result, coarse coal particles that were previously lost to tailings are forced to the overflow with the clean coal concentrate. It should be noted that this is not a flotation process. Without the upward fluidization water, the bubble-particle aggregate will not have sufficient buoyancy to rise to the top of the separator. The bubble-particle aggregate behaves as a single entity with a lower specific gravity.

To illustrate the advantage of the HydroFloat in fine coal recovery, a series of in-plant tests were conducted on a central Appalachian coal. Tests were conducted using a 30-cm (12-inch) diameter pilot-scale separator at feed rates ranging from 15-25 tph/m^2 (1.5-2.5 tph/sqft). In this evaluation, the HydroFloat was operated with and without air injection. In the absence of air, the HydroFloat operates as a teeter-bed separator. The results from these tests are shown in Figure 12. It can be seen that the HydroFloat is able to achieve a higher product mass yield at the same product quality (ash content). The improvement is attributed to increased recovery of the coarse, low-density coal particles. In fact, washability analysis of the separated products indicated that the HydroFloat recovered approximately 30 percent more of the +1.6 s.g. particles in the +35 mesh size fraction.

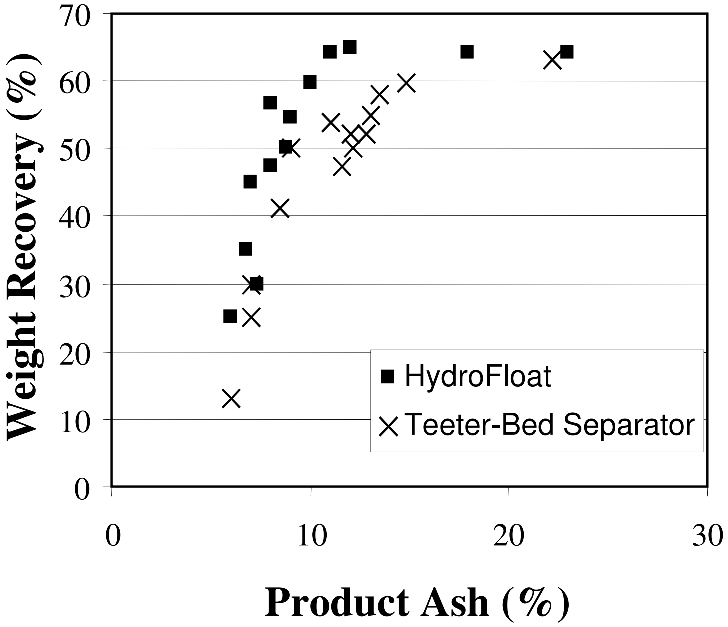

Figure 12. Clean Coal Mass Recovery versus Product Ash Content for Teeter Bed and HydroFloat Separators.

CONCLUSIONS

A new separator, known as the HydroFloat, has been developed to overcome some of the shortcomings associated with traditional separation processes for recovering coarse particles. The novel characteristic of this separator is the formation of a hindered "teeter" bed of fluidized solids into which small air bubbles are introduced. The bubbles attach to hydrophobic particles and create light bubble-particle aggregates that can be separated from hydrophilic particles based on the principle of differential density. Benefits of this new separator include enhanced bubble-particle contacting, better control of particle residence time, lower axial mixing/cell turbulence, and reduced air consumption.

Laboratory tests were conducted to evaluate the potential of this new technology for upgrading mineral samples from various sources (e.g., phosphate matrix, potash, feldspar, and coal). The test data indicate that the HydroFloat cell is capable of increasing coarse particle recoveries by 20% over conventional separation approaches. Furthermore, the concentrate grades were also improved in some cases due to a reduction in coarse particle misplacement.

Based on the success of the laboratory test work, pilot studies were undertaken for three specific applications: phosphate, potash, and coal. In each case, tests were conducted using larger scale separators capable of processing up to 6 tph. The results from each application indicate that the HydroFloat can achieve a substantially higher recovery at the same product grade as compared to current plant performance. A summary of the findings from these studies is presented in Table 1.

Table 1. Summary of Results from HydroFloat Plant Studies.

Application	**Feed Rate (tph)**		**Recovery (%)**		**Grade (%)**	
	Current	**HydroFloat**	**Existing**	**HydroFloat**	**Existing**	**HydroFloat**
Phosphate	10 tph/m^2	25 tph/m^2	91	98	4-6$^{(1)}$	4-6$^{(1)}$
Potash	7 tph/m^2	16 tph/m^2	50	90	60$^{(2)}$	57$^{(2)}$
Coal	3tph/start	20 tph/m^2	50	60	8-10$^{(3)}$	8-10$^{(3)}$

(1) Percent Insols; (2) % K_2O; (3) % Ash

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