

# IMPLEMENTATION OF THE HYDROFLOAT TECHNOLOGY AT THE SOUTH FORD MEADE MINE

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## ABSTRACT

Several industrial-scale HydroFloat separators have recently been installed at Mosaic's South Fort Meade beneficiation plant for the purpose of improving phosphate recovery and throughput capacity. This technology was implemented after numerous laboratory, bench-scale, and on-site, pilot-scale test campaigns. The results from this detailed test work provided sufficient justification for the complete retrofit of the existing coarse and ultra-coarse flotation cells. Data indicate that the metallurgical results obtained with the full-scale separators are consistent with that obtained during both the bench- and pilot-scale evaluations. The apparent benefits, theory of operation, and commissioning of the equipment are also discussed.

## INTRODUCTION

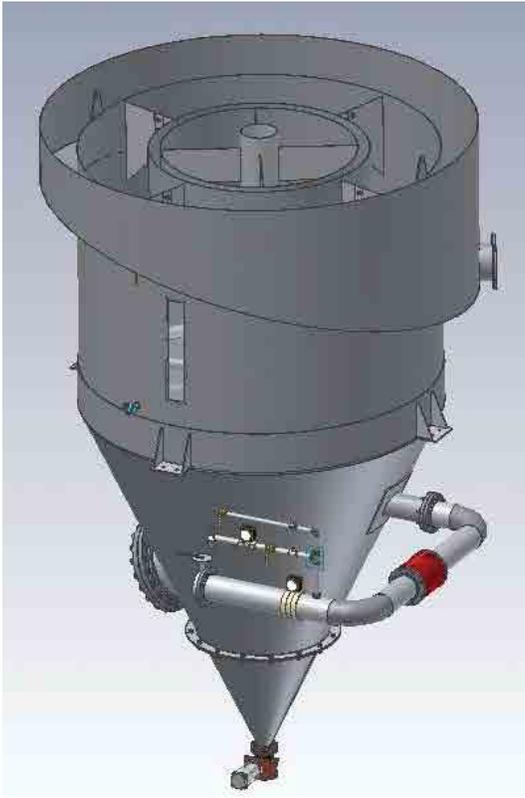
The HydroFloat is an air-assisted, hindered-bed (i.e., teeter-bed) separator. These teeter-bed separators are commonly used in the minerals industry for both particle classification and gravity concentration. The specific usage is highly dependent on the hindered-settling velocity of particles as described by:

$$U_t = \frac{gd^2 (\phi_{\max} - \phi)^\beta (\rho_s - \rho_f)}{18\eta(1 + 0.15Re^{0.687})} \quad [1]$$

in which  $g$  is the acceleration due to gravity,  $d$  is the particle size,  $\rho_s$  is the density of the solid particles,  $\rho_f$  is the density of the fluidized suspension,  $\eta$  is the apparent viscosity of the fluid,  $Re$  is Reynolds number,  $\phi$  is the volumetric concentration of solids,  $\phi_{\max}$  is the maximum volumetric packing, and  $\beta$  is a constant and dependent on Reynolds number ( $Re$ ).

This equation, advocated by Kohmuench et al. (2002), indicates that the settling velocity of a particle in a hindered-settling environment is primarily a function of both particle size and density. Inspection of Equation [1] indicates that a teeter-bed separator can be efficiently utilized as a classifier when the density distribution of the ore is relatively tight. Similarly, a tight size distribution allows these devices to be utilized as gravity separators.

However, when used as gravity separators, these devices can suffer from the misplacement of low-density coarse particles to the high-density underflow. This shortcoming is due to the accumulation of coarse lowdensity 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 elutriation 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.



**FIGURE 1**  
Model of a Full-Scale HydroFloat Separator

The HydroFloat presented in Figure 1, which has been described elsewhere (Kohmuench et al., 2002), is a device that was developed to overcome these shortcomings. This apparatus is a hybrid density separation device whose theory of operation is based on flotation fundamentals. The separator operates much like a traditional hindered-bed classifier 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. As the air bubble dispersion rises through the teeter-bed, the bubbles become attached to the hydrophobic particles, thereby reducing their effective density. 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.

Throughout the development of this technology, Eriez Manufacturing has conducted testing for various applications including coarse phosphate recovery. This testing has ranged from industry-sponsored research projects (Mankosa et al., 2002) to privately funded, short-term test programs carried out at various industrial beneficiation plants. The most complete test program was completed for The Mosaic Company's South Fort Meade Mine. In this instance, pilot-scale testing was carried out after a successful round of laboratory-scale evaluations. After providing sufficient justification, several full-scale HydroFloats were installed as retrofit systems. Compared to the traditional technology, the HydroFloat offered several advantages including enhanced bubble-particle contacting, better control of particle residence time, lower axial mixing and cell turbulence, and reduced air consumption. These advantages translated to an immediate increase in circuit capacity for both the coarse and ultracoarse flotation circuits.

## 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:

$$P = P_c P_a (1 - P_d) \quad [2]$$

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:

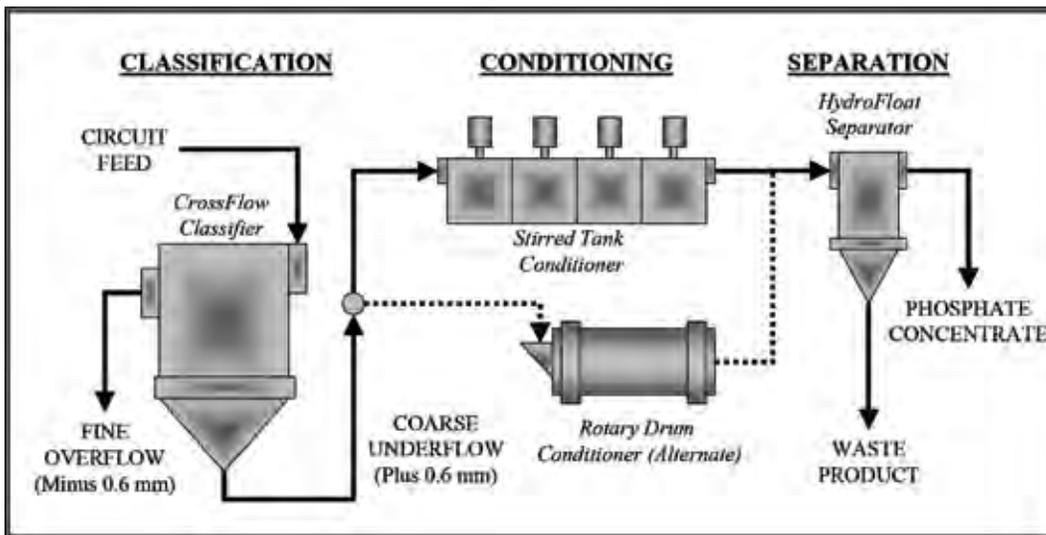
$$P_d = (D_p/D_p^*)^x \quad [3]$$

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. 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.

Furthermore, 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. 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.

In addition, the hindered-bed environment 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.

The HydroFloat is also not restricted by the buoyancy limitations



**FIGURE 2**  
Typical Flowsheet for Concentration of Coarse Phosphate

found in traditional flotation equipment. These limitations are typically encountered as particles make the transition between the pulp and froth interface after the successful attachment of an air bubble. For instance, a 3-mm bubble has sufficient buoyancy to float a 3-mm particle within the pulp ( $SG = 1.05$ ). In contrast, the bubble-particle aggregate does not have sufficient buoyancy to be transported through the froth which is comprised predominately of air ( $SG = 0.20$ ). However, the HydroFloat is operated without a traditional froth and provides a continuous overflow, thus negating these transport limitations. Furthermore, due to the large size of the treated particles, multiple bubbles and other bubble-particle aggregates can combine to improve the probability of recovery by increasing both buoyancy and particle drag induced by the teeter-water flow.

## APPLICATION BACKGROUND

Prior to marketing, 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 +1.2-mm (+14 mesh), highgrade pebble product. The screen underflow is subsequently deslimed at 0.100-mm (150 mesh) to remove ultra-fine clays. Although 20-30% of the phosphate contained in the matrix is present in the ultra-fine fraction, technologies currently do not exist that permit this material to be recovered in a cost-effective manner. The remaining 1.2x0.100-mm (14x150 mesh) fraction is typically classified into 1.2x0.425-mm (14x35 mesh) coarse and 0.425x0.100-mm (35x150 mesh) fine 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 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 fraction. Typically, the coarse flotation unit operation occurs after classification and conditioning of the ore as seen in Figure 2. Sizing is usually carried out using hydraulic teeter-bed separators followed by conditioning at high percent solids in either stirred-tank or rotary tumbling conditioners. After proper conditioning, separation of the coarse concentrate follows.

Coarse Matrix		Ultra-Coarse Matrix	
(mm)	(% in Class)	(mm)	(% in Class)
+1.00	3.3	+1.20	5.2
1.00 x 0.710	11.9	1.20 x 1.00	7.5
0.710 x 0.425	48.6	8	29.1
-0.425	36.2	-0.850	58.2

**TABLE 1**  
Typical Coarse and Ultra-Coarse Matrix Feed Size Distributions

Test No.	Product*		Reject*		Recovery*	
	BPL	Insol	BPL	Insol	Mass	BPL
Coarse						
1	64.9	9.0	0.4	97.0	38.0	99.0
2	66.2	8.6	0.4	96.9	37.2	98.9
3	66.2	7.7	0.4	97.0	37.2	98.9
4	66.4	8.0	0.4	97.0	37.1	98.9
5	67.3	7.3	0.4	97.0	36.6	98.9
<b>Avg.</b>	<b>66.2</b>	<b>8.1</b>	<b>0.4</b>	<b>97.0</b>	<b>36.3</b>	<b>98.9</b>
U-Coarse						
1	67.7	9.4	0.7	96.6	30.0	97.7
2	65.5	11.2	1.1	96.3	30.5	96.3
3	66.1	10.1	1.0	96.1	30.3	96.6
4	65.7	10.6	1.1	95.6	30.4	96.3
5	66.5	10.8	1.6	97.3	29.5	94.6
6	67.9	9.5	1.3	96.2	29.2	95.5
7	66.1	11.5	1.2	97.3	30.1	95.9
8	68.4	9.4	0.9	96.4	29.4	97.0
9	67.4	9.5	1.5	97.4	29.2	94.9
10	67.3	9.2	0.8	98.0	30.0	97.3
<b>Avg.</b>	<b>66.9</b>	<b>10.1</b>	<b>1.1</b>	<b>96.7</b>	<b>29.9</b>	<b>96.2</b>

\* (%)

**TABLE 2**  
Laboratory-Scale Results for Coarse (24.9% BPL) and Ultra-Coarse (20.8% BPL) Testing

This typical flowsheet is common for the phosphate industry as well as other mineral applications including, but not limited to, silica sands, potash, and feldspar. In fact, a full-scale recovery circuit identical to that seen in Figure 2 is currently being employed for the recovery of 2.0x0.5-mm diamonds.

## LABORATORY-SCALE TESTING

Following the general flowsheet in Figure 2, laboratory-scale evaluations were conducted on two size fractions of phosphate ore provided by the Mosaic Company's South Fort Meade Mine (SFM). These fractions included a "coarse" and "ultra-coarse" matrix nominally consisting of 0.710x0.425-mm (24x35-mesh) and 1.20x0.710-mm (14x24-mesh) particles, respectively. Typical size distributions are provided in Table 1.

The laboratory testing was carried out using a 100-mm (4-inch) diameter Plexiglas bench-scale test unit. The feed was preclassified prior to arrival at Eriez and subsequently reagentized in a batch rotary conditioner. The feed rate to the HydroFloat was metered through the use of a vibratory feeder and tests were conducted as a function of several operating parameters including air rate, teeter-bed level, reagent rate, and feed rate. The results from this laboratory-scale testing are presented in Table 2. The reagent utilized in this test work was a fatty acid and fuel oil blend (FA/FO) and averaged an addition rate of 0.4-0.5 kg/tonne (0.8-1.0 lb/ton) for these evaluations.

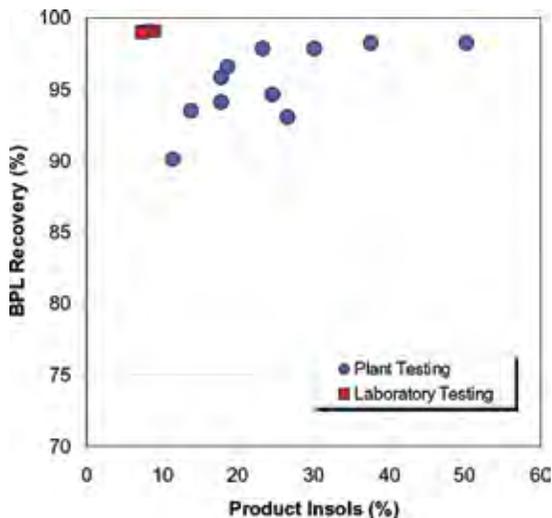
The coarse matrix was successfully concentrated as presented in Table 2. While the feed contained a phosphate content of 24.9% as measured as *Bone Phosphate of Lime* (BPL), the concentrates produced averaged 66.2% BPL for all tests. The average product contained only 8.1% insols (i.e., silica) at a BPL recovery of nearly 99%. Similarly, the ultra-coarse matrix was upgraded from a feed BPL of 20.8% to an average of 66.9%. In this case, the product contained 10% insols, on average, while recovering over 96% of the available BPL.

## PILOT-SCALE TESTING

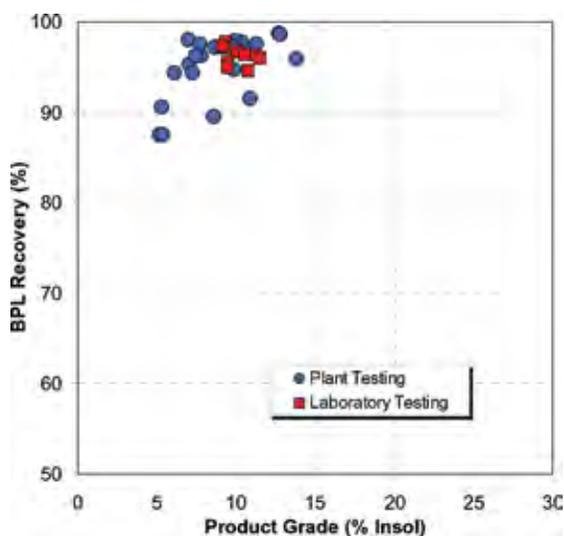
After the successful laboratory-scale test run, pilotscale evaluations were required to provide scale-up and design criteria. The pilot-scale work also allowed for the use of plant water, which typically causes a reduction in flotation performance due to the presence of clay slimes, algae and other plant growth, and residual chemicals. These evaluations were completed using a 300-mm (12-inch) diameter HydroFloat complete with PID level control and instrumentation.

Feed to the pilot-scale test unit was obtained from the outlets of the stirred-tank-conditioners feeding both the coarse and ultra-coarse circuits. The feed was introduced into the pilot-scale cell via gravity and regulated through the use of a manual control valve. Reagent levels were adjustable and controlled through the plant PLC system. As such, tests were conducted as a function of reagent rate as well as other adjustable operating parameters such as aeration rate, teeter-bed level, and feed rate. For these tests, reagent rates were varied from a low of 0.40 kg/tonne (0.80 lb/ton) to 0.60 kg/tonne (1.20 lb/ton).

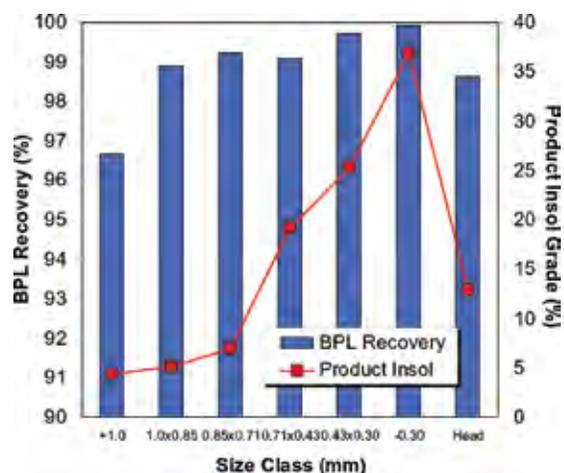
Presented in Figure 3 are the results for the test work conducted on the coarse flotation feed stock. For this test work, BPL recovery ranged



**FIGURE 3**  
Coarse Pilot- and Lab-Scale Results



**FIGURE 4**  
Ultra-Coarse Pilot- and Lab-Scale Results



**FIGURE 5**  
Size-by Size Results for Pilot-Scale Test Work

from 90% to a high of 98% with an overall average grade of 60% BPL and less than 20% insols. At maximum separation efficiency, the total insol rejection ranged between 75% to 85% resulting in a high grade phosphate product. Figure 3 also indicates that the results from the laboratory evaluation were superior to those produced for the plant trials. This finding was found to be a direct result of the varying size distributions of the feed treated. In fact, it was found that the material used in the laboratory testing contained virtually no misplaced fine material while the feed used in plant trials was significantly finer. As such, a portion of the -0.425-mm material present in the plant feed stream was entrained into the float product through hydraulic carryover or through the activation and subsequent flotation of the finer insols. This finding was little cause for concern given the high BPL recovery of the HydroFloat system and the fact that the coarse product is subsequently routed to amine flotation for grade control.

The results for the ultra-coarse on-site testing are presented in Figure 4. Due to the nearly limitless amount of available feed material, the full flotation response curve was generated during the plant trials. For this stream, BPL recoveries ranged from 88% to 98%, depending on operating conditions. The average product grade ranged between 5% and 13% insols, by weight. Furthermore, the resultant product BPL grade ranged between 64% and 69%. Unlike in the coarse circuit, the ultra-coarse product is not routed through the amine flotation circuit for grade control; therefore, a high-grade product is a requirement. Figure 4 also indicates that there is a high degree of consistency between the plant and laboratory testing for this ultra-coarse material.

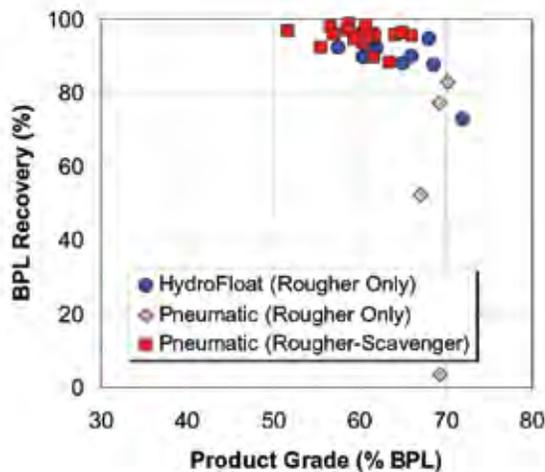
Also determined during the ultra-coarse plant trials were size-by-size recovery data as presented in Figure 5. During the test work, composite samples of sufficient quantity were generated to allow for BPL and insol assays for the various size fractions. The samples were assayed and the resultant data were material balanced for consistency. As shown in Figure 5, the HydroFloat achieved significant recovery for all size classes up to and including material coarser than 1-mm (16-mesh). For all size classes, the BPL recovery exceeded 95% while still maintaining a product grade of approximately 12% insols. As expected, the insol content of the coarser size fractions were superior to that found in the finer fractions. The elevated insol content of these finer fractions was a direct result of hydraulic entrainment and signify the importance of efficient sizing prior to the HydroFloat. Regardless, the final product grade for this example exceeded 67% BPL.

## FULL-SCALE SEPARATORS

The pilot-scale test work indicated that the HydroFloat separator would provide superior metallurgical results when compared to the existing plant equipment. Other benefits were also predicted including increased capacity and lower overall reagent rates. Preliminary estimates indicated that the surfactant (i.e., frother) usage would be decreased by 22% and 40% for the coarse and ultra-coarse circuits, respectively. Furthermore, it was also predicted that the addition rate of the fatty acid and fuel oil blend would be decreased by nearly 40% for both circuits. Based on this information, several HydroFloat units were installed at South Fort Meade as retrofits. These retrofits



**FIGURE 6**  
Coarse HydroFloats with Instrumentation



**FIGURE 7**  
Data from Coarse Rougher Start-Up

took advantage of the existing tank structures that were already in place and being utilized as pneumatic, eductorstyle flotation columns.

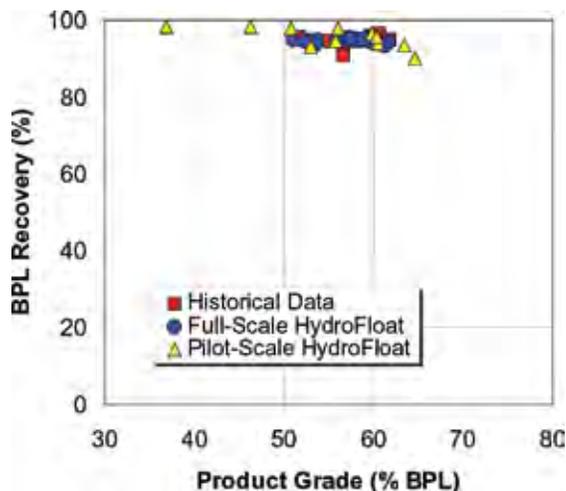
A single HydroFloat was initially installed to treat coarse feed. The original coarse circuit was designed to process approximately 160 tph and was configured as two parallel rougher-scavenger unit operations with a total of four cells. Initially, a single 2.5-meter (8-ft) diameter rougher unit was retrofit so that the HydroFloat concept could be confirmed on a full-scale basis. Specifically, the original pneumatic cell was stripped of all instrumentation and internal components. A new internal teeter-water and air distributor were installed along with internal launders, a new feed injection well, internal dewatering cone, and any required instrumentation. A retrofit coarse unit is shown in Figure 6. Once complete, the new cell was commissioned and thoroughly tested with regard to capacity and optimum reagent levels.

The results from this commissioning effort are provided in Figure 7. As shown, the single HydroFloat rougher cell provided metallurgical results superior to the pneumatic rougher flotation cell installed on a parallel coarse feed stream. In fact, while the HydroFloat provided BPL recoveries approaching and exceeding 90%, the existing cells struggled to achieve 80% BPL recovery in a single stage. More importantly, the single HydroFloat cell provided results nearing the performance of the combined rougher-scavenger pneumatic cells. It should be noted that during this commissioning process, test data indicated that a feed rate of 20 tph/m<sup>2</sup> (2.0 tph/ft<sup>2</sup>) was obtainable. Due to these results, the process of converting the remaining three cells to HydroFloats was initiated.

Upon the complete retrofit of the remaining coarse cells, the circuit feed was increased over 50% from 145 tph (160 stph) to 227 tph (250 stph). Presented in Figure 8 are the data from the pilot-scale testing alongside that collected from the complete full-scale HydroFloat coarse circuit. Besides the good correlation between the pilot- and fullscale data, it should be noted that with the increased feed tonnage to the circuit, there has been no deterioration in metallurgical performance when compared to the available historical data as seen in Figure 8.

Following the installation of the coarse circuit HydroFloats, the ultra-coarse circuit was also upgraded. In this case, there were eight 1.2-meter (4-ft) diameter units to be retrofit. The initial stage included de-commissioning all eight of the existing pneumatic cells and then installing four (4) ultra-coarse HydroFloat units. Data from this phase of the upgrade indicated that the four HydroFloats were able to successfully treat the same tonnage previously treated by the original eight pneumatic flotation cells. A single retrofit unit is shown in Figure 9.

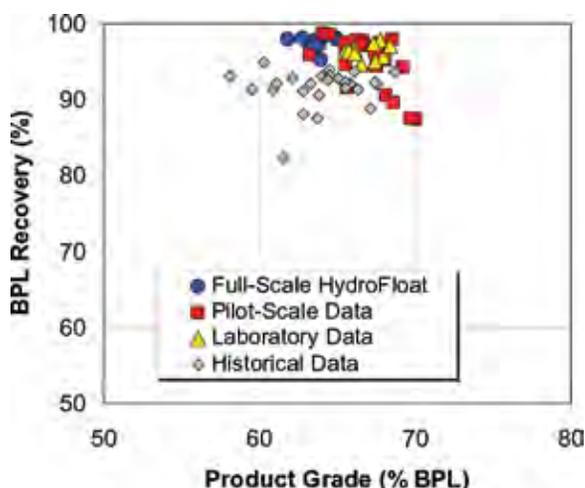
The ultra-coarse upgrade was finalized with the addition of the remaining four cells. Soon after, optimization of the circuit was completed at a new circuit feed rate of 118 tph (130 stph) versus a previous rate of 60 tph (65 stph). Data from the circuit optimization is provided in Figure 10 and shows a very good correlation between the lab-, pilot-, and full-scale metallurgy. BPL recovery for this circuit now averages 97% at a product grade of 64% BPL. The full-scale data also compares favorably with the historical data for this circuit. In fact, the quality of the ultra-coarse product improved slightly while the overall BPL recovery has increased an average of 6.5%.



**FIGURE 8**  
Full-Scale Coarse HydroFloat Results



**FIGURE 9**  
Ultra-Coarse HydroFloat with Instrumentation



**FIGURE 10**  
Full-Scale Ultra-Coarse HydroFloat Results

In addition to the consistent or improved metallurgy, the anticipated reduction in reagent addition was also confirmed. Table 3 indicates that while the overall circuit tonnages have been significantly increased, the various reagent addition rates have indeed improved. Specifically, the fatty acid and fuel oil blend (FA/FO) was reduced nearly 10% for the coarse circuit and nearly 38% for the ultra-coarse circuit. Reductions in surfactant rates were also confirmed and are the result of the lower water addition rates utilized with the HydroFloat retrofits when compared to the previous pneumatic cells.

The addition of fuel oil (FO) has been reduced in the coarse circuit, but surprisingly, it has increased in the ultracoarse circuit. Prior to the upgrade, no additional fuel oil was utilized; however, fuel oil is now required to achieve the maximum separation efficiency. This increase appears to be a direct result of non-optimal conditioning as the upstream stirred-tank conditioners are being run at lower-than-ideal percent solids in order to prevent sanding. As a consequence, additional fuel oil must be added to overcome the wet conditions and improve dispersion of the collector.

## SUMMARY

Several conclusions can be drawn from the results provided throughout the laboratory-, pilot-, and full-scale test work. These include:

1. The HydroFloat separator provides a metallurgically efficient means of upgrading coarse phosphate sands. The theory of operation shows that by attaching an airbubble to a reagentized or naturally hydrophobic particle, a density separation can be achieved within a teeter-bed based separator.
2. Laboratory-scale testing indicated that the HydroFloat is able to recover both coarse and ultra-coarse particles at BPL recoveries of 99% and 96%, respectively. For this test work, the product grade averaged approximately 66% BPL.
3. Follow-up pilot-scale testing confirmed the laboratory results. Both high BPL recoveries and product grades were achieved while testing both a coarse and ultracoarse matrix.
4. The full-scale installations of the coarse and ultracoarse HydroFloats have confirmed that these units deliver metallurgical results consistent with both the laboratory- and pilot-scale test units. This indicates that the scale-up for the HydroFloat is relatively straightforward and results from small-scale units can be utilized for predicting full-scale performance.
5. Four (4) coarse HydroFloat retrofits were successfully installed and are able to treat 56% more material than the previously installed pneumatic cells. While the metallurgy is consistent, the fatty acid, fuel oil, and surfactant addition have all been reduced significantly, resulting in considerable cost savings.
6. The eight (8) ultra-coarse HydroFloat retrofits were successfully installed and are treating 86% additional tons than the previously installed pneumatic cells. In this case, the HydroFloat is achieving an additional 6.5% BPL recovery while operating with a 37% reduction o collector (FA/FO).

<b>Circuit</b>	<b>Feed (Rate)</b>	<b>FA/FO (%)</b>	<b>FO (%)</b>	<b>Surfactant (%)</b>
Coarse	+56%	-9.8%	-8.6%	-56.7%
U-Coarse	+86%	-37.4%	+100%	17.3%

**TABLE 3**

Comparison of Feed and Chemical Rates for the Coarse and Ultra-Coarse HydroFloat Circuits

## ACKNOWLEDGMENTS

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