Improving coarse particle flotation using the HydroFloat™ (raising the trunk of the elephant curve)

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ABSTRACT

The copper sulfide processing flowsheet has remained virtually untouched for decades and follows a logical progression – crush, grind, float, regrind and refloat to produce a final copper concentrate. This well-defined and proven method of copper sulfide processing has served the industry well for over a century and is based on the particle size range for which conventional flotation is most effective. Work by numerous experts has shown that mechanical flotation works well for a limited size range, from approximately 15 to 150 μm, and is best presented in the well-recognized “elephant curve.” Particles outside this critical size range are typically lost in industrial operations and rejected to tailings due to inherent constraints associated with the physical interactions that occur in the pulp and froth phases of conventional flotation equipment.

The underlying mechanisms responsible for the decline in flotation recovery of very fine and very coarse particles have been extensively discussed in the technical literature. For coarser particles, low recovery is typically attributed to both turbulence and buoyancy constraints. To overcome these inherent limitations found in conventional flotation cells, Eriez has developed and successfully implemented a technology, the HydroFloat™, that combines the aspects of fluidized-bed separation and flotation. More recently, this same technology has been demonstrated in sulfides for recovering coarse value from concentrator tails. Other efforts have shown the positive benefit that can be derived from implementation within the concentrator itself. This paper will discuss the theory of operation of fluidized-bed flotation and data from various applications are presented.

1. Coarse particle flotation

Improving the recovery of coarse particles (+0.150 mm) has been a long-standing goal within the minerals processing industry. The relationship between particle size and floatability was presented early in the literature based on research conducted by Gaudin et al. (1931) which showed that coarse particles are more difficult to recover than intermediate size particles. The reduction in recovery for coarse particles is often attributed to detachment due to excessive turbulence within conventional mechanical flotation cells.

The typical drop off in recovery for coarse sulfide particles within industrial flotation plants is best illustrated by the size-by-size flotation data reported by Lynch et al. (1981) in the well-recognized “elephant curve” shown in Fig. 1. More recent size-by-size recovery data show little has changed in the past several decades to expand the applicable size range of froth flotation when upgrading sulfide minerals. 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 coarsest fractions that have been discarded as refuse (Mankosa et al., 2016a).

The reduction in recovery for coarse particles is often attributed to detachment due to excessive turbulence within conventional mechanical flotation cells. Prior work by Soto and Barbery (1991) has shown that conventional flotation cells operate with contradictory goals: (1) provide enough agitation to maintain all the particles in suspension, (2) shear and disperse air bubbles, and (3) promote bubble-particle collision. However, this approach is counterproductive for the recovery of coarse particles which requires a quiescent system for minimizing detachment.

In addition to turbulence, surface expression of the mineral of interest can also create challenges when treating coarse particles. It is commonly accepted that liberation or, more accurately, mineral surface expression, increases with decreasing particle size. A higher surface expression provides more sites for bubble attachment. Additionally, minimal surface expression for particles coarser than 150–200 μm can create a situation where the strength of bubble/particle attachment is low. This condition reinforces the need for a non-turbulent flotation environment.

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Theoretical and experimental studies conducted by researchers indicated that the inherent limitations of conventional flotation can be overcome through the utilization of a fluidized-bed flotation machine specifically engineered for the selective recovery of feeds containing very coarse particles. The HydroFloat™ separator was the first embodiment of this approach and was specifically designed in the early 2000s (Mankosa and Luttrell, 2002) to address the limitations of traditional flotation systems. By using a quiescent, aerated fluidized bed, the turbulence commonly found in a mixed-tank contacting environment is greatly minimized. As a result, delicate bubble-particle aggregates are more likely to report to the concentrate without disruption. Furthermore, the absence of a continuous froth phase minimizes drop back that can occur at the pulp/froth interface.

A simplified schematic of the HydroFloat™ fluidized-bed separator is provided in Fig. 2. As shown, the device consists of a circular tank subdivided into an upper freeboard compartment, a middle separation chamber and a lower dewatering cone. Similar to a typical hindered-bed separator, feed solids are introduced just above the middle separation chamber and are permitted to settle against an upward rising current of water or other fluidizing medium. The upward flow creates a fluidized “teeter bed” of suspended particles with high interstitial liquid velocities that resist the penetration of slow settling particles. Gas, controlled using a flow control valve and flow meter, is then introduced and dispersed along with frother into the fluidization network through an externally located high-shear sparging system. As the air bubbles rise through the teeter bed, they become attached to hydrophobic particles, thereby reducing their effective density and simultaneously increasing their buoyancy. 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 where they accumulate due to their lower density.

Particles having minimal hydrophobic surface exposure with bubble attachment are very effectively prevented from being lost to tailings by the action of the teeter bed. The accumulated aggregates lift off the teeter-bed interface and are carried upward through the freeboard compartment due to increased buoyancy created by the initial and, potentially, subsequent bubble attachment. The bubble-particle aggregates are then rapidly carried by the rising flow of fluidization water upward through the freeboard compartment where they overflow into a collection launder. Due to the constant overflow of fluidization water, only a thin froth layer forms at the top of the flotation pulp. Hydrophilic particles that do not attach to the air bubbles (i.e., rock) continue to move down through the teeter bed, settle into the dewatering cone, and are discharged through the use of an underflow control valve. The flow through the underflow nozzle is automatically controlled based on readings from an electronic level indicator located on the lower wall of the separations chamber.

![Fig. 1. Conventional flotation data for industrial sulfide flotation circuits (Lynch et al., 1981).](image)

![Fig. 2. Simplified schematic of the HydroFloat™ separator with bubble-particle aggregates shown (inset).](image)
2. Theory

The concept of bubble-particle attachment in a rising current separator has been previously demonstrated (Barbery, 1989; Laskowski, 1995). Unfortunately, these previous attempts used an open-column operating in the free, not hindered, settling regime. As a result, these configurations did not have the advantages associated with a fluidized-bed separator. Under free settling conditions, individual particles do not affect the settling behavior of adjacent particles and, as such, the pulp has the rheological characteristic of the fluid. Furthermore, the settling velocity is determined solely by the particle size and particle density. Fluidized-bed separators are fundamentally different. At high solids concentrations, adjacent particles collide with each other influencing the settling characteristics. The settling path is greatly obstructed reducing particle velocity.

Additionally, the high solids concentration increases the apparent viscosity and specific gravity of the pulp, thus further reducing the particle settling velocity. As a result, the acceleration of particles becomes more important than the terminal velocity. This collision phenomenon is the most important aspect of hindered settling and provides favorable hydrodynamic conditions that cannot be achieved in open-tank reactors, such as conventional, mechanical cells. Fluidized-bed flotation offers several additional important advantages for treating coarse feed streams. While discussed in-depth elsewhere (Kohmuench et al., 2010), a summary of these include:

- **Improved Attachment**: The differential velocity between bubbles and particles is greatly reduced by the hindered settling/rise conditions within a fluidized-bed flotation device. Consequently, the reduced velocity will increase the contact time between bubbles and particles, thereby promoting the probability of collection and enhancing flotation recovery. This phenomenon is particularly important for coarse particles. The high solids concentration within the teeter bed will also improve recovery by increasing the collision probability between bubbles and particles (Yoon and Luttrell, 1989). In the fluidized-bed flotation device, this phenomenon occurs due to the compression of the fluid streamlines around the bubbles as they rise through the teeter bed. The increased probability of collision provides reaction rates that are several orders of magnitude higher than those found in conventional flotation.

- **Reduced 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. This study concluded that the maximum size of particles that can be recovered by flotation increases by more than an order of magnitude when changing from highly turbulent to quiescent conditions. Woodburn et al. (1971) and Schultz (1984) have also shown that reduced cell turbulence significantly increases the maximum particle size limit for effective flotation. The use of fluidization water in a fluidized-bed flotation device makes it possible to keep particles dispersed and in suspension without the intense random agitation required by mechanical flotation machines.

- **No Buoyancy Limitation**: A fluidized-bed flotation cell is both a flotation device and a density separator. The use of a teeter bed makes it possible to achieve separations based on small differences between the density of free suspended particles and the density of bubble-particle aggregates. As a result, separations can be achieved even if the buoyancy of the bubble-particle aggregate is too small to lift the aggregate from the surface of the teeter bed. Furthermore, the HydroFloat™ operates with only a minimal froth layer. This operating characteristic nearly eliminates the buoyancy limitation and is particularly important for very large particles which would be difficult to recover in conventional flotation machines that operate with froth depths ranging from 100 to 900 mm.

Recovery is also enhanced through the creation of the previously described bubble clusters. To form these clusters, a single bubble-particle aggregate combines with supplementary bubbles and particles to form the larger flocs. While the literature indicates that large bubble-particle clusters do improve the overall buoyancy of the coarse particles (Ata et al., 2009), it should be noted that these larger flocs also induce a considerable amount of drag when compared to a single bubble and particle, especially within systems that incorporate a significant degree of negative bias (i.e., fluidization flow). The large cross-sectional area presented by the flocs increases the drag force and improves the probability that the larger clusters will not settle into the aerated teeter bed, but be transported to the product launder.

- **Plug-Flow Conditions**: Fluidized-bed separators operate under nearly plug-flow conditions because of the low degree of axial mixing afforded by the uniform distribution of particles across the teeter bed. Consequently, the cell operates as if it were comprised of a large number of cells in series. Provided that all other conditions are equal, this characteristic allows a single unit to achieve the same recovery as a multi-cell bank of conventional cells (Arbiter and Harris, 1962; Mankosa et al., 1992). In other words, this approach ensures that more of the available cell volume is effectively used when compared to well-mixed conventional cells or open columns.

- **Increased Retention Time**: In most flotation processes, feed particles move with the fluid flow towards the discharge point (co-current mode). In contrast, the approach demonstrated in Fig. 1 shows particles moving in the opposite direction to the fluid flow. This counter-current mode has obvious advantages since the effective settling velocity of the particles is reduced by the upward flow of liquid. In addition, the hindered settling conditions within the teeter bed never allow the particles to achieve their terminal free-fall velocity. Therefore, the fluidization water provides a significant increase in the particle retention time. The longer retention time allows good recoveries to be maintained without increasing cell volume.

- **Reduced Maintenance Requirements**: With a tank design based on hindered-settling reactors, there is no need for mechanical agitation and thus, there are no internal moving (wear) parts. As a result, equipment maintenance is substantially reduced. Water and air introduction is metered using traditional flow meters and controlled using industry standard control valves.

Initially, the HydroFloat™ was developed to provide a solution for poor coarse phosphate recovery; however, the first full-scale industrial unit (3-meter diameter) was installed and commissioned at PotashCorp’s Rocanville potash mill to treat approximately 125 t/h of coarse tailings from existing conventional cells. Test work showed that by using this approach, the recovery of potash could be increased from approximately 50% to over 90% (Kohmuench and Thanasekaran, 2013; Potash Beneficiation, 2004). Since that time, there have been numerous successful installations of this technology throughout the industrial minerals sector. This includes a nearly plant-wide retrofit installation at Mosaic’s South Fort Meade Mine (Kohmuench et al., 2007) and at PotashCorp’s Aurora beneficiation plant (Piegols et al., 2015). At South Fort Meade, the capacity of the two coarse flotation circuits were
improved dramatically with a simultaneous increase in phosphate recovery and significant reduction in reagent addition rate. At the Aurora plant, the implementation of this technology represented an additional recovery of 11,000 t/month of coarse phosphate which would have otherwise reported to tailings. In addition to fertilizer minerals, the HydroFloat™ has been commercially used to recover vermiculite in the United States, diamonds in Canada, and spodumene in Australia. Initial application of this technology to industrial minerals was reasonable given the relatively large particle sizes treated in flotation, coarse liberation characteristics, and generally lower specific gravities relative to polymetallic ores. However, research efforts have quickly focused on sulfide and base metal applications due to the recognized increase in capacity and associated energy savings (Awatey et al., 2015, 2013; Fosu et al., 2015).

3. Sulfide applications

Several researchers are now investigating the possibilities and significant benefits that can be realized with the proper application of this approach as it pertains to metalliferous ores, base metals, and sulfides. In fact, researchers at the University of Newcastle (Jameson, 2014) have confirmed that the low turbulence environment afforded by an aerated teeter bed can improve coarse particle recovery. These researchers have patented a similar device (Jameson et al., 2007) with the only substantial difference being that the latter invention provides for a distinct froth phase. The effect of maintaining a froth on coarse particle recovery has been explored elsewhere (Mankosa et al., 2016b; Kohmuench et al., 2010). These studies indicate that a large particle is not likely to be recovered as it will have insufficient buoyancy to transfer from the pulp into the froth.

Most recently, Miller et al. (2016) confirmed through high-resolution X-ray microtomography (HRXMT) that fluidized-bed flotation was able to recover metalliferous values at a grind size much coarser than that treated in industrial concentrators. By using HRXMT to identify the surface properties of the products produced by both the HydroFloat™ and a conventional cell, Miller et al. was able to compare the cumulative frequency of particles of varying liberation appearing in both the concentrate and tailings (Fig. 3b). Using this approach, it was shown that fluidized-bed flotation was able to recover nearly 100% of the 0.850 × 0.500 mm multiphase particles containing as little as 1% surface exposure of sulfide mineral. In fact, the data indicate that the tailings contained virtually no particles containing more than 1.5% exposed sulfide grain surface area. This is further illustrated in Fig. 3a which shows a photo of +0.250 mm concentrate particles collected from a pilot-scale HydroFloat™ which was treating copper tailings. The photograph shows the low expression of sulfide minerals on the surface of coarse particles that were lost using conventional flotation. However, the low surface expression was still sufficient for these particles to be recovered using fluidized-bed flotation. Many test programs are now underway that are looking to exploit the HydroFloat’s™ ability to recover coarse particles with minimal hydrophobic surface expression.

3.1. Scavenging

To demonstrate the effectiveness of the HydroFloat™ separator for recovering lost values from tailings, a 5 t/h pilot plant was designed, constructed, installed and tested at an industrial copper concentrator site in South America. The pilot-plant flowsheet, which is shown in Fig. 4, consisted of classification and flotation equipment that was designed based on the data gathered from an initial laboratory-scale test program. While the primary thrust of the investigation was to determine the viability of using fluidized-bed flotation for the enhanced recovery of coarse particles, supplementary equipment was installed to demonstrate that additional fine sulfides (< 0.050 mm) could be scavenged from the same tailings stream. Additional detail on this test work is offered elsewhere (Mankosa et al., 2016a).

During operation of the pilot plant, a representative feed sample was extracted from the existing tailings flume at the industrial concentrator and pumped to an agitated feed sump. The slurry was then pumped to a 250-mm diameter classifying cyclone to make a primary size separation. The cyclone underflow stream discharged to a well-mixed feed sump and was pumped to a 0.5-m square CrossFlow™ hindered-bed classifier. The cyclone was added to the pilot-plant design to provide a bulk initial size separation prior to the final high-efficiency classification step using the CrossFlow™ separator. The fine cyclone overflow was combined with the CrossFlow™ overflow and directed to a conditioning tank. The conditioned fine feed was pumped to a set of 0.5-m diameter by 3-m tall columns configured in a rougher/scavenger circuit. The coarse underflow (P80 = 0.300 mm) from the CrossFlow™ was conditioned and fed to a pair of 0.3-m diameter HydroFloat™ flotation cells. Note that while a secondary HydroFloat™ separator was included in the flowsheet, it was found that little additional recovery was achieved by employing a scavenger step. The coarse flotation concentrate was conveyed to 0.3-m diameter x 1.0-m long ball mill in closed circuit with a high-frequency Derrick™ screen. Conditions were established to produce a cleaner flotation feed of suitable grind size (P80 = 80 µm). The ball mill discharge was combined with the fine concentrate from the column circuit and fed to conditioning tanks.

![Fig. 3. Example of (a) particles recovered by the HydroFloat™ with minimal surface expression and (b) deportment as a function of sulfide surface expression (after Miller et al., 2016).](image-url)
followed by cleaner flotation columns.

A parametric test program was established to evaluate the overall circuit performance, though only the performance of the coarse flotation circuit is considered in this work. As such, the primary objective was to assess if fluidized-bed flotation is economically capable of recovering coarse copper and molybdenum values that are currently lost to tailings at the industrial concentrator. Timed samples of feed, product and tails from each unit operation were collected to determine solid/liquid flow rates. The samples were assayed for copper, molybdenum, iron and sulphur. All results were mass balanced to assess the validity of each test sequence properly.

The results from the pilot-scale test program are summarized in Fig. 5a and indicate that this goal was largely achieved. Noting that approximately 60% of the feed copper value reported to the classifier underflow, the data indicate that 35.8% of the copper (up to 60% unit Cu recovery) was recovered by a single-stage HydroFloat™. Molybdenum unit recovery was also high and exceeded 80%. Fig. 5b provides data from a long-term test where the test cell operated in a stable and consistent manner in a plant environment, even when treating a highly variable tailings slurry. It should be noted that the numbers above do not reflect losses that will occur in the final copper/moly cleaning circuit. Preliminary work indicates that copper cleaner circuit recovery will be in the range of 80–85% for this particular feedstock. This work is currently underway and will be presented in Fig. 4.

Fig. 4. Schematic diagram of pilot test circuit for copper sulfide tailings treatment.
future publications. Regardless, the results shown in Fig. 5 clearly illustrate the scavenging ability of the HydroFloat™ separator when reprocessing coarse tailings.

It should be noted that the coarse reject stream still contained some copper, but SEM images indicated that there was no presence of copper remaining on the particle surfaces. In other words, the HydroFloat™ was able to capture nearly 100% of the copper that was available for bubble attachment. Any remaining copper was essentially locked and encapsulated. This finding is illustrated by the SEM pictures offered in Fig. 6 and Fig. 7 which show the coarse (+0.250 mm) product and tails, respectively, produced from the test unit.

In this examination, the coarse samples were inspected under an SEM microscope using backscattering technology (Energy Dispersive X-ray Spectroscopy). In this case, surface copper would reflect a blue color while an orange color was utilized for indicating Molybdenum values. As seen in Fig. 6(a), only relatively small points of copper exposure are present on the particle surfaces. This reaffirms that only a minimal amount of sulfide exposure is necessary for recovery using fluidized-bed technology and that these composites will require further liberation to achieve the necessary grade. Additionally, this technology provides a second chance to recover liberated material that was not recovered using the conventional flotation machines such as the coarse Molybdenum as seen in Fig. 6(b). In contrast, the same SEM examination was also conducted on the coarse tailings produced by the HydroFloat™. In this case, no copper or molybdenum was found to be present on the surface of any particles in the tailings as seen in Fig. 7(a) or (b). Since this sample did contain copper and molybdenum as indicated by assay, it was concluded that these values were locked and contained within the particles.

### 3.2. Split-feed flotation

One particularly exciting configuration is to use fluidized-bed flotation technology to reject well-liberated siliceous gangue from primary grinding circuits at a relatively coarse size, thereby making room for new feed tonnage in the primary grinding circuit. For example, consider the hypothetical base-sulfide flowsheet shown in Fig. 8(a). This simplified flowsheet includes a primary grinding mill, primary classifying cyclones, rougher-scavenger flotation banks, cleaner flotation columns and a middlings regrind mill. In this simplified example, the primary grinding mill may, in fact, be a secondary ball mill. In any case, the availability of fluidized-bed flotation technology allows the circuit to be modified as shown in Fig. 8(b). Many permutations of this approach are possible including directing the HydroFloat™ overflow to the regrind mill instead of the primary grinding mill. Each circuit variation will have to be examined based on existing equipment and the level of gangue rejection that can be achieved.

In the case of Fig. 8(b), the primary classifying cyclones are reconfigured to provide a substantially coarser size cut (e.g., D80 increased from 200 to 300 μm). This layout allows the primary cyclone underflow to be passed back to the primary mill, while the overflow is passed to a secondary set of classifying cyclones. The secondary cyclone bank manages the relatively high volume while producing a fine (e.g., minus 200 μm) overflow that is sufficiently liberated to be upgraded by the downstream conventional/column flotation circuit and a coarse (e.g., plus 200 μm) underflow that is passed to the HydroFloat™ circuit. In this case, feed to the HydroFloat™ is reclassified using a CrossFlow™ separator to ensure near-complete removal of fines. The HydroFloat™ is then used as a highly efficient scavenger to ensure that all particles containing valuable sulfide mineral report to the overflow concentrate which is recycled back to the primary grinding mill for further size reduction and liberation.

In this arrangement, the HydroFloat™ underflow, which consists of coarse liberated gangue, is rejected as a throw-away product that is essentially free of valuable mineral. This siliceous gangue tonnage makes room for new feed tonnage in the primary grinding mill. In other
words, this proposed HydroFloat™ circuit is designed to reject large tonnages of well-liberated siliceous gangue that often consumes a large volume of the circulating load in primary grinding circuits. The replacement of coarse circulating gangue with fresh feed dramatically increases concentrator capacity with only a modest investment in new equipment for classification and flotation. In fact, simulation and modelling work conducted based on experimental data generated from various bench- and pilot-scale test campaigns indicates that this circuit configuration can increase concentrator capacity by 20–25% (Mankosa et al., 2016b).

Data from a 2014 investigation is offered to illustrate this point. This test campaign was initiated by a copper producer interested in improving coarse particle recovery in the concentrator (72,000 t/d). The plant regularly experiences a significant drop in total copper recovery when processing ore with a high native copper content. During these times, total copper recovery can be as low as 60%. In response, the copper producer evaluated different options to improve recovery during these operating periods including the use of centrifugal gravimetric concentrators, flash flotation, additional conventional flotation cells, and chemical reagent changes. Unfortunately, these options have not achieved the needed results. As such, the goal of this investigation was to evaluate the effects of fluidized-bed flotation technology with regard to the potential improvements in native copper recovery and plant capacity.

Feed samples were obtained from the hydrocyclone underflow used to close a production ball mill grinding circuit. Large bulk samples were obtained and then representative subsets were screened into the required size fractions (1.0 × 0.180 mm and 0.850 × 0.180 mm). The ore was predominately a copper sulfide, but also contained varying amounts of native copper. Feeds with large amounts of native copper were considered High Native Copper Containing (HNCC) ores while feeds having little native copper were termed Low Native Copper Containing (LNCC) ores. For these tests, the copper ore had to be properly reagentized. In this case, a Xanthate (Z-6) was used in combination with dithiophosphate to activate the copper for flotation. In fact, simulation and analysis (MLA) were performed which confirmed the very complex mineralogy of the feed samples used in this test work. The liberation characteristics for this ore are considered very poor. Regardless, the microscopic study and mineral liberation analysis indicated that fluidized-bed flotation selectively floated coarse particles which are not considered floatable in the plant using the existing conventional flotation techniques. The microscopic analysis indicated that fluidized-bed flotation selectively floated native copper particles in excess of 0.800-mm diameter. Further, these studies indicated there were zero native copper particles present in the tailings samples and any copper losses were due to significant locking of sulfide particles. Even with poor liberation, upgrade ratios ranging between 4 and 24 were achieved.

As seen in Fig. 9, copper recoveries for this on-site testing effort fluctuated between 71% and 89% depending on the ore processed and the various operating conditions. Most importantly, it was found that the total copper recovery when treating the HNCC ore was 15–25 percentage points higher than that achieved in the industrial plant when processing the same ore type. Further, copper recovery was not compromised by the inclusion of the 1.0 × 0.850 mm HNCC fraction as demonstrated by the composite data. Selectivity was also not sacrificed as the mass yield of the float concentrate ranged between 4% and 15%.
the plant operating cost. Additional tests are to be performed to determine if slightly finer grinding will further optimize these results and minimize any locked losses in the final coarse tailings stream.

3.3. A complement to flash flotation

It is very important to note that the proposed fluidized-bed flotation circuit shown in Fig. 8b is not “flash flotation” where an attempt is made to remove liberated sulfide minerals that are trapped in the classifying circuit of a primary grinding mill due to their higher density. This approach is typically utilized because it prevents over-grinding of classifying circuit of a primary grinding mill due to their higher density. This approach is typically utilized because it prevents over-grinding of the sulfide minerals. However, recent work conducted by Newcrest Mining Limited (Seaman and Vollert, 2017) proposed that fluidized-bed flotation may well complement traditional flash flotation circuitry as each is effective over different particle size ranges. This work concluded that the application of the HydroFloat™ can successfully provide the opportunity to improve global recovery and allow for early gangue rejection for particles ranging between 100 and 600 μm.

The Newcrest effort showed that high recoveries for gold were realized for multiple samples from early laboratory work, an on-site pilot campaign, and an in-depth off-site pilot effort. Results, shown in Fig. 10, ranged from 80% to nearly 95% gold recovery for a particle size range, nominally 600 × 150 μm. Data showed that the size-by-size recoveries for these various efforts were all very similar, decreasing below 80% only for particles coarser than 300 μm. While more variable, the gold recovery for the + 425 μm material ranged between 60 and 80%. Even at greater than 600 μm, gold recovery was in excess of 50%. Most importantly, detailed results indicated that the overall free gold recovery was 98% with losses only in the finest fraction caused by surface coatings. The typically hard to float flattened and platey gold was easily recovered using fluidized-bed flotation.

The Newcrest work also included a comparison between the Eriez HydroFloat™ and both traditional flash flotation and typical gravity results provided by Laplant and Dunne (2002). This comparison, shown in Fig. 11, illustrates that fluidized-bed flotation may provide a good solution in “flash” flotation circuits where the particle size is too coarse for traditional flash-flotation cells and not coarse enough for gravity circuits. In fact, this comparison shows that the HydroFloat™ provided significantly higher recoveries, than flash flotation when treating material at 100 μm. Further, the HydroFloat™ provided higher recoveries than that demonstrated by gravity concentrators up to approximately 600 μm.

4. Summary & conclusions

Current flotation practice can be improved by applying flotation fundamentals to fluidized-bed separation. This novel approach was utilized in the development of the HydroFloat™ air-assisted teeter-bed separator which uses flotation within a fluidized-bed environment to improve the recovery of coarse particles. The quiescent nature of a teeter-bed separator increases the overall flotation rate and level of recovery by utilizing efficient mixing conditions, increased retention time, reduced detachment (i.e., low turbulence), and improved collision rates when compared to conventional flotation cells.

More than 40 full-scale HydroFloat™ units have been successfully installed within the industrial minerals market. Due to that success, test work continues to be carried out for metalliferous ores. The results from multiple on-going, site-based test campaigns and laboratory-based investigations indicate that the particle size range for successful flotation can be increased dramatically using this technology – even with a minimal exposure of hydrophobic grain surfaces. Data continue to show that fluidized-bed flotation can increase coarse particle recovery and improve process economics by capturing particles that would require significantly more grinding or otherwise be lost when using traditional flotation methods.

Most recently, potential applications of this innovative technology in the sulfide minerals industry have been considered. This was demonstrated through multiple test programs on both copper and gold which clearly show a high degree of recovery can be obtained for particles up to 0.850 mm. These data also indicate that significant savings can be realized through the rejection of well-liberated siliceous gangue that would otherwise consume capacity in the grinding circuit.

A demonstration pilot plant was commissioned to treat tailings from a copper concentrator. The coarse values recovered using this innovative technology were captured from a stream just prior to discharge into an impoundment. These values, some with minimal exposed sulfide surface expression, were predominantly coarse, low-grade sulfides that had not been recovered using the conventional cell technology installed in the main concentrator. Data show that substantial gains can be achieved using this novel approach to recover values previously discarded to a typical sulfide tailings stream.

The data generated from these laboratory and pilot testing efforts have been used to model and simulate innovative flotation circuits which have been designed to take advantage of the benefits afforded by fluidized-bed flotation technology. Process economics can be vastly improved by capturing particles that would either require significantly
more grinding or be lost when using traditional flotation methods. In fact, one study indicated that the capacity of a primary grinding circuit can be increased by 20–25% for a hypothetical concentrator treating a typical porphyry copper ore.

As this technology progresses, it provides process engineers with another tool for circuit optimization where the engineered solution includes less grinding, increased capacity, higher recovery and, most importantly, reduced costs. 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 from ore reserves by extending the trunk of the “elephant” curve.

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