

A NEW PARADIGM IN SULFIDE PROCESSING

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BACKGROUND

It has long been established that copper sulfide processing 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. The justification for this approach is well based as conventional flotation technology has a defined particle size range over which it can effectively recover floatable particles. Work by numerous experts has shown that currently available flotation technology is effective over a size range of approximately 15 to 150 microns. An example of these findings is shown in the well-recognized “elephant curve” (Figure 1). Particles outside this critical size range are typically lost in industrial operations and rejected to tailings streams due to inherent constraints associated with the physical interactions that occur in the pulp and froth phases of conventional flotation equipment.

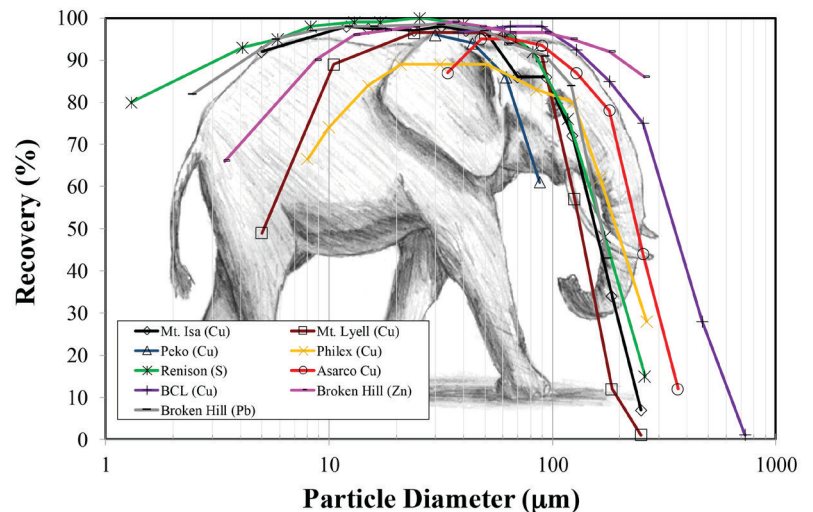


FIGURE 1
Conventional flotation data for industrial sulfide flotation circuits (Lynch et al., 1981).

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 finer particles, lower recovery is typically attributed to low bubble-particle collision rates that reduce the probability of attachment. Low collision rates for finer material can generally be overcome by utilizing equipment that improves the flotation rate. Flotation rate can be increased by increasing the total surface area of air that is rising through the flotation cell by reducing the bubble diameter (i.e., micro- or pico-bubbles) or by increasing the gas rate. Even with the generation of smaller bubbles, recovery can still be challenging

as longer retention times are typically required for finer particles. Further, the recovery of very fine material is also negatively impacted with the trend of utilizing larger and fewer cells in order to reduce capital costs as any gains are typically lost due to inefficient mixing conditions.

In contrast, the reduction in recovery for coarse particles is often attributed to detachment due to excessive turbulence within conventional mechanical flotation cells. Prior work 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 dealing with 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 200 micron can create a situation where the strength of bubble/particle attachment is low. This condition reinforces the need for a non-turbulent flotation environment.

As mining markets continue to reset after the most recent boom/bust cycle, 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. 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 both ends of the "elephant" curve.

COARSE PARTICLE FLOTATION

The question of how to improve recovery over a wider particle size range parallels the age-old adage "How do you eat an elephant?" The answer, of course, is one bite at a time. Using this approach, Eriez® Flotation Division has developed a split-feed flowsheet incorporating two novel flotation technologies: the HydroFloat™ separator for coarse particle recovery (>150 microns) and the StackCell™ to improve fine particle recovery (<15 microns). The split-feed circuit approach was selected to allow incorporation into plants operating with existing technology. By classifying flotation feed at a point where coarse recovery deteriorates (approximately 150 microns), the existing flotation circuit can be optimized to recover the minus 150 micron fraction while passing the plus 150 micron material forward to a different coarse flotation circuit.

Coarse particle flotation has been an area of significant interest for many investigators over the decades. Most industrial minerals producers (phosphate, potash, etc.) deal with this on a regular basis as their ore, unlike porphyry copper ores, liberates at a very coarse size. In fact, in most fertilizer applications, it is not unusual to have liberated material as coarse as 2-3 millimeters. Traditionally, producers have handled this problem by using conventional flotation technology and running the cells in a "near

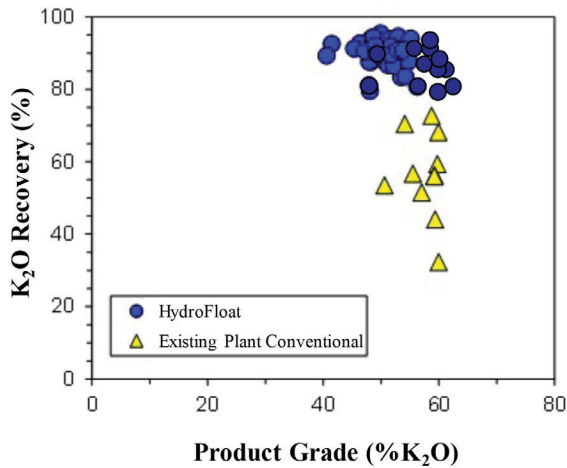


FIGURE 2
a) Typical response curve for coarse potash flotation using Eriez HydroFloat™ separator, b) Potash concentrate photo with 3/8-inch (9.5-mm) bolt shown for scale.

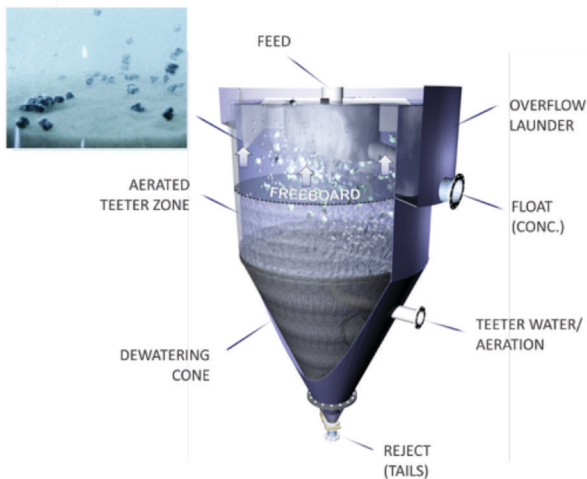


FIGURE 3
Cut-away view of Eriez HydroFloat™ separator.

“spillover” configuration to ensure recovery of the coarse material. As one might expect, however, this mode of operation results in a great deal of non-selective carryover of fine gangue material.

In the early 2000s, engineers at the Eriez Flotation Division (EFD) introduced an entirely new generation of flotation equipment to the minerals processing industry (Mankosa and Luttrell, 2001). This unique technology, which is currently marketed under the trade name HydroFloat™, was specifically developed to address and overcome the longstanding shortcomings of conventional machine designs in floating very coarse particles. Extensive lab- and pilot-scale testing at various plant sites demonstrated the technology to industry supporters. The machine has had a successful impact in several sectors of the industrial minerals market for the collection of very coarse particles that were once believed to be unrecoverable by froth flotation technology. As an example, typical results from a coarse potash flotation circuit are provided in Figure 2. As shown, K₂O recovery was improved from an average of 60 percent to approximately 90 percent for material with a top-size approaching 4 millimeters.

As shown in Figure 3, the HydroFloat™ separator consists of an open tank subdivided into three sections. During operation, deslimed feed slurry is introduced into the upper section of the tank. At the same time, a regulated flow of process water is added just above the bottom cone section of the tank through a network of distribution pipes. The upward flow of water creates a fluidized bed of suspended particles consisting primarily of non-floating (tailings) solids. Finely dispersed bubbles generated by the sparging system are carried by the fluidization water into the fluidized bed where they are efficiently forced into contact with the densely-packed particles. Upon attachment to hydrophobic particles, the resulting bubble-particle aggregates are carried by the rising flow of fluidization water into the overflow launder. Hydrophilic solids continue to pass through the fluidized bed and accumulate in the dewatering cone located below the water distribution network and subsequently discharged. Because of the unique design features, the HydroFloat™ separator offers several important advantages for treating coarser feed. One of the most obvious issues addressed by the HydroFloat™ technology is the challenge of overcoming negative bubble-particle buoyancy.

Figure 4 clearly highlights the issue of bubble-particle buoyancy. Examination of the photo in Figure 4b illustrates how the lower density of the froth phase can create a barrier to the recovery of coarse particles. The photograph shows a large bubble-covered particle that has sufficient buoyancy to float to the pulp/froth interface, but too little buoyancy to transfer up through the froth phase. The lower curve plotted in Figure 4a effectively illustrates the impact of this phenomenon for a case in which the froth density at the base is assumed to be 90% gas by volume ($\rho_f=0.1 \text{ gm/cm}^3$). As expected, the maximum size that can rise through this low-density phase is greatly reduced even for low-density particles. For the case of chalcopyrite ($\rho_p=4.2 \text{ gm/cm}^3$), the froth transfer limitation would theoretically only allow particles smaller than 290 microns to be recovered using 1 mm bubbles. The attachment of multiple bubbles to the particle can help minimize this problem, although this is difficult for coarse, poorly liberated solids that have only a small patch of exposed

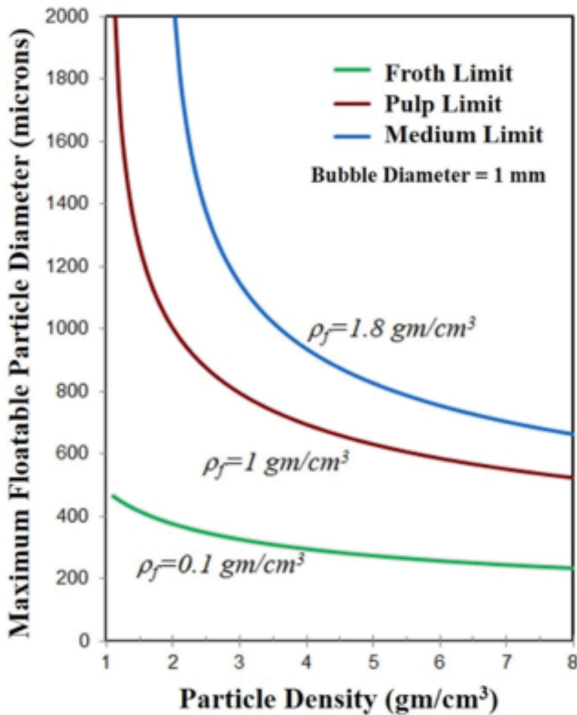


FIGURE 4

a) Maximum floatable particle size as a function of density, and b) Photo of froth buoyancy limitation.

mineral surface available for bubble attachment. In the HydroFloat™ unit, this limitation is eliminated since the machine operates in overflow mode without a froth-pulp transfer restriction. While the buoyancy analysis has been greatly simplified for the sake of brevity, it should be apparent that the intentional elimination of a distinct froth phase of discernable depth and the creation of a fluidized bed of solids make it possible for the HydroFloat™ technology to recover much larger particles than traditional froth flotation machines.

Another unique characteristic of the HydroFloat™ separator is the bubble/particle contact mechanism within the aerated fluidized bed of solids. The hindered settling condition within the fluidized bed substantially reduces the differential velocity between bubbles and particles, which in turn increases the contact time and likelihood of successful adhesion between bubbles and hydrophobic particles. The high solids concentration within the teeter bed also improves the attachment rate by increasing the collision frequency between bubbles and particles. The increased probability of collision results in reaction rates that are several orders of magnitude higher than conventional flotation machines. The high solids content of the fluidized bed also increases the particle residence time by decoupling the flow of solids from the flow of liquid. In most flotation processes, feed particles move with the fluid flow towards the discharge point in a co-current action. In contrast, particles move in the opposite direction to the fluid flow in the HydroFloat™ system. Therefore, the fluidization water provides a significant increase in the particle retention time. The longer retention time provides higher recovery without increasing cell volume. The HydroFloat™ also operates 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. In other words, the HydroFloat™ separator makes more effective use of the available cell volume.

Lastly, the HydroFloat™ operates with a very low degree of pulp turbulence. The use of a fluidized bed in the HydroFloat™ separator makes it possible to keep particles dispersed and in suspension without the intense agitation required by mechanical flotation machines. As such, the low turbulence within the HydroFloat™ separator is an ideal hydrodynamic environment for maximizing bubble-particle contacting while minimizing particle detachment.

FINE PARTICLE FLOTATION

The fine end of the elephant curve (~150 microns) continues to be hotly contested by the biggest flotation machine suppliers. The race continues to provide bigger and bigger machines to increase capacity and reduce the total number of units required. Economics associated with plant design typically lean toward fewer, large-volume cells. These large cells (500 cubic meters and larger) are challenged by the high cost of on-site fabrication, high power consumption (>500 kW) and extreme facility requirements (building height) to allow for maintenance. The latter

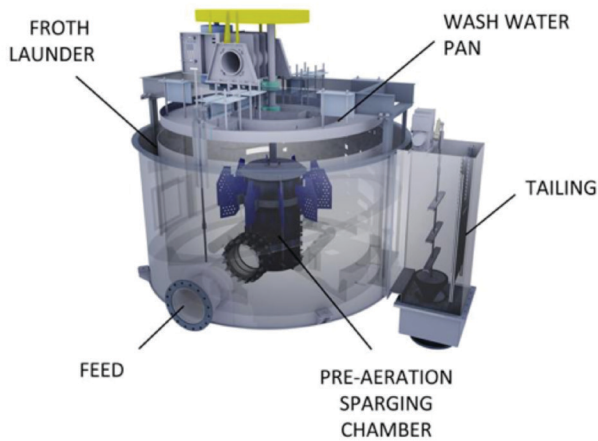


FIGURE 5
Three-dimensional view of a StackCell.

constraints are particularly problematic in areas with high energy costs and excessive seismic activity.

These concerns illustrate the need for a new generation of flotation machine that offers comparable metallurgical performance while improving upon the design and operational challenges of traditional flotation circuits. Based on the experience gained over the last decade with the design, engineering, and operation of column flotation circuits, Eriez has developed a new high-capacity flotation cell that offers a reduction in both size and horsepower. The Eriez StackCell™ (Figure 5) represents a leap in technology based on the application of flotation fundamentals. Additionally, the unit achieves comparable metallurgical performance with reduced capital, installation, and operating costs.

The StackCell™ design takes advantage of a patented independent contacting chamber. Feed slurry and air enter this chamber and are subjected to intense shear mixing to generate bubbles and provide contacting with the hydrophobic species. Particle collection is achieved in this section and the slurry is subsequently discharged into a quiescent phase separation chamber. The separators are specifically designed to have both a small footprint and operate with a gravity-driven feed system that allows cells to be easily “stacked” in-series or placed ahead of existing conventional or column flotation cells.

A unique feature of the StackCell is the method of sparging which utilizes a high-shear, bubble-particle contactor in lieu of the conventional rotor-stator mechanism historically utilized in mechanical flotation cells. Instead of operating with a large tank volume, the StackCell™ forces the bubbles and particles to contact in a small confined volume. Under this highly turbulent environment, the flotation rate constant has been shown to be a function of the concentration of bubbles, the concentration of particles and the specific energy imparted to the system. The high-shear environment within the aeration chamber provides an energy dissipation level that is substantially greater than that produced by conventional flotation machines, thereby enhancing the recovery of difficult-to-float fine particles. The contactor is specially designed to efficiently impart energy for bubble-particle contacting and to avoid unnecessary pumping or unwanted recirculation of the feed slurry. This approach provides a focused energy input used for gas dispersion and contacting and not for particle suspension. Moreover, the intense mixing shears the low-pressure air blown into the machine into extremely small bubbles, which substantially increases the concentration of bubbles present in the contacting chamber. This feed pre-aeration approach ensures that the maximum concentration of floatable particles and gas bubbles are present during the high-shear contacting.

The significance of this approach can be better understood when one realizes that flotation recovery is directly proportional to the flotation rate and particle retention time. Intense, high-shear contacting dramatically increases the flotation rate due to the extreme increase in energy density. By increasing the flotation rate several fold, retention time can be correspondingly reduced. As a result, the size of the flotation machine can be significantly reduced while still achieving the same metallurgical performance. In fact, results indicate that total circuit retention time can be less than forty percent that required by existing conventional flotation

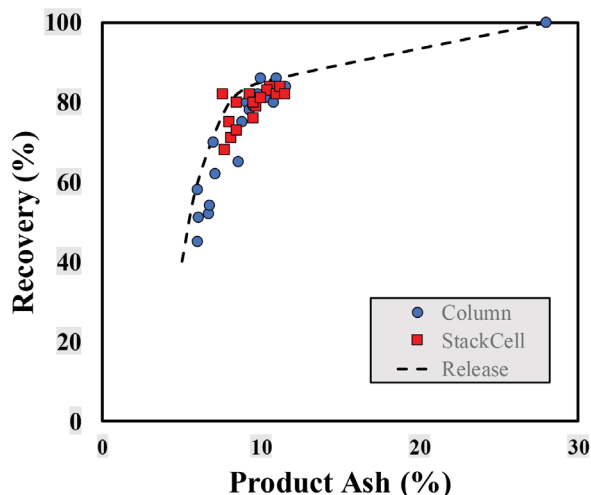


FIGURE 6
Product grade versus recovery curve for StackCell™ in comparison with column and release analysis results.

technology. Therefore, structural, foundation and all ancillary service costs are dramatically reduced. Likewise, there is a considerable reduction in the overall plant space required – area as well as height. It should be noted that the StackCell is less than three meters in height (see Figure 5). Therefore, the design height for crane access is substantially reduced.

Lastly, it should be noted that operating costs are also substantially lower. In conventional flotation cells, a significant portion of the energy input is used to maintain particles in suspension as opposed to being focused on bubble/particle contacting. In the StackCell™, the energy is focused specifically on creating bubbles within the aeration chamber. Therefore, the total energy input to the system is approximately half that required by conventional machines.

The StackCell™ was initially developed as a high-efficiency, low-energy substitute for column flotation cells in coal applications in the early 2000s. Because the unit incorporates wash water, it is able to achieve similar metallurgical performance. As with most new technology, it was introduced to industry through extensive laboratory- and pilot-scale testing at customer sites. High unit capacity and a small footprint made this technology particularly attractive for the coal industry as plants are typically very space constrained. Initial success with this technology led to the installation of more than thirty cells at multiple sites over the past decade. Typical results for a commercial StackCell™ installation for fine coal flotation are shown in Figure 6. For comparison, results from a pilot-scale column test as well as a standard laboratory release analysis test are also shown. The release analysis test is a recognized industry standard for determining the baseline “best performance” for flotation separation in coal. Findings demonstrated that the StackCell™ was able to achieve the desired metallurgical performance in this application using half the space and power.

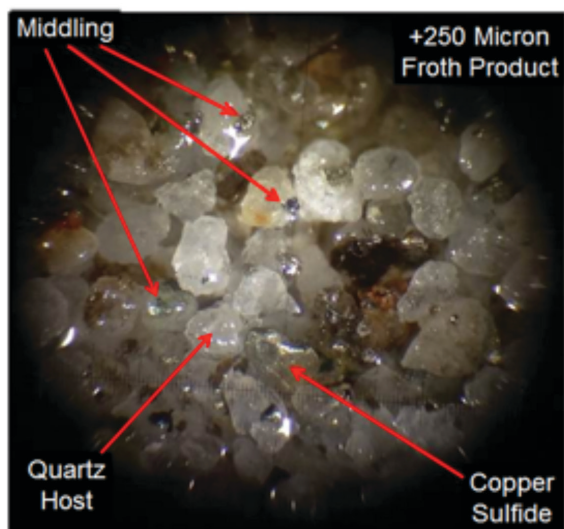


FIGURE 7
Photo of middling particles recovered from tailings using the HydroFloat™ technology.

SPLIT FEED CIRCUIT FOR COPPER SULFIDES

Based on the success of these technologies in coal and industrial minerals, multiple laboratory- and pilot-scale studies were initiated on copper sulfide ores. Results indicate that this technology can be used to extend the recovery versus size curve (Figure 1) on both ends. Extensive test work on copper sulfide tailings streams indicates that additional values can be extracted (copper and molybdenum) from the fines fraction using the high-capacity StackCell technology.

As significant, data collected from pilot-scale tests conducted at base metal concentrators in North America, South America and Australia confirm that the HydroFloat™ technology can float sulfide middlings particles as large as 850 microns. Figure 7 shows an example of plus 250 micron sulfide concentrate particles collected from tests conducted on an active tailings stream. The photograph shows the low expression of sulfide minerals on the surface of coarse particles that were lost in the primary conventional flotation circuit. However, the low surface expression (containing as little as one percent exposed sulfide mineral) was sufficient for these particles to be recovered using the HydroFloat™ separator (Miller et al, 2016).

PRIMARY CONCENTRATOR APPLICATIONS

This game-changing result provides an opportunity to rethink current industry practice which, in addition to achieving significant liberation, must grind to a size which is optimum for existing flotation technology, i.e., <150 microns. One particularly exciting retrofit opportunity is to use the HydroFloat™ 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.

As an example, consider the hypothetical base-sulfide flowsheet shown in Figure 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. The availability of the HydroFloat™ technology allows the circuit to be modified as shown in Figure 8(b). In this case, the primary classifying cyclones are reconfigured to provide a substantially coarser size cut (e.g., D80 increased from 200 to 300 microns). This layout allows the 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 produces a fine (e.g., -150 micron) overflow that is sufficiently liberated to be upgraded by the downstream conventional/column flotation circuit and a coarse (e.g., nominal +150 micron) underflow that is passed to the HydroFloat™ circuit. In this case, feed to the HydroFloat™ is reclassified using a CrossFlow™ hindered-bed separator to ensure near-complete removal of fines. The HydroFloat™ is then used as a highly efficient coarse particle flotation cell to ensure that all sulfide minerals are recovered. The concentrate is recycled to the primary grinding mill for further size reduction. Alternatively, depending on capacity, this stream could also be sent to the existing regrind circuit.

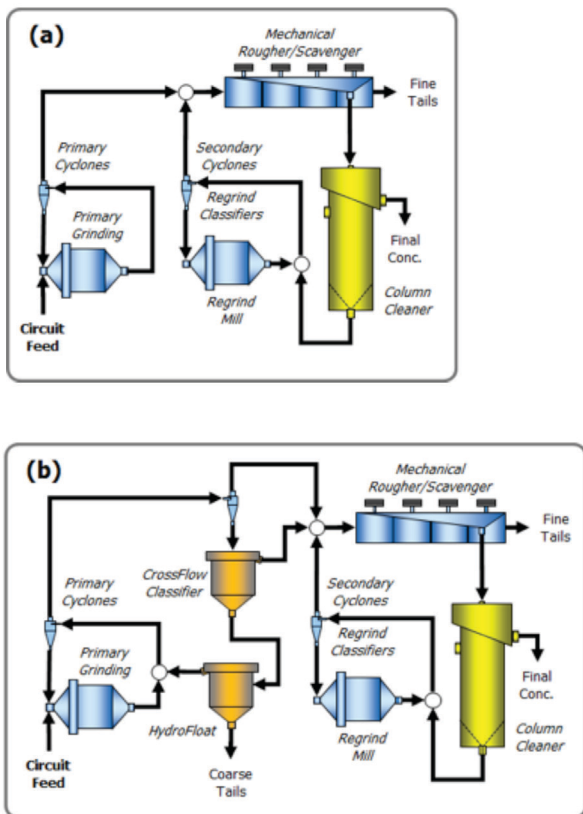


Figure 8

Examples of (a) the simplified baseline flowsheet and (b) modified split-feed flowsheet incorporating the HydroFloat™ technology.

The HydroFloat™ underflow, which consists of coarse liberated gangue, is rejected as a throw-away product that is either 1) essentially free of valuable mineral or 2) contains such a low amount of mineral value that it is uneconomical to process further. As such, the gangue rejected by the HydroFloat™ makes room for new feed tonnage in the primary grinding mill. It should be noted that the proposed HydroFloat™ circuit is not “flash flotation” as has been advocated in the past. Flash flotation attempts to remove fast-floating, liberated sulfide minerals that are trapped in the classifying circuit of a primary grinding mill due to their shape and/or higher density. While this prevents over-grinding of the sulfide minerals, this does little to improve mill capacity. In contrast, the proposed HydroFloat™ circuit is designed to reject large tonnages of well-liberated gangue that often consumes a large volume of the circulating load in primary grind circuits. The replacement of coarse circulating gangue with new fresh feed provides an opportunity for the proposed circuit to dramatically increase concentrator capacity with only modest investments in new equipment for classification and flotation.

The flowsheets shown in Figure 8 have been the subject of an extensive recent study (Mankosa et al, 2016). In this study, a split-feed circuit was modeled to demonstrate how the HydroFloat™ technology can be used to increase the capacity of a primary grinding circuit for a hypothetical concentrator treating a typical porphyry copper ore. Results demonstrate

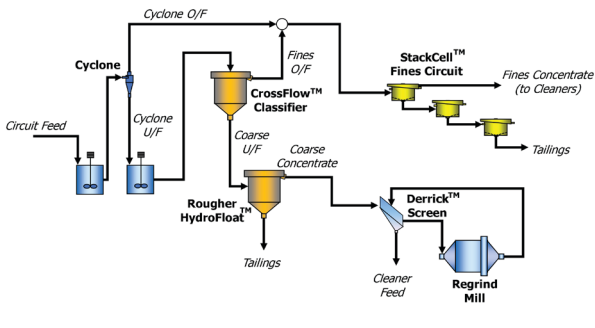


Figure 9
Pilot HydroFloat/StackCell™ flowsheet for tailings retreatment.



Figure 10
Installation photos for Eriez split-feed pilot plant.

that the proposed circuit configuration can reject coarse well-liberated gangue that would otherwise occupy the capacity of the primary grinding mill. The simulation data demonstrated that a 20-25% increase in concentrator capacity can be achieved without the addition of new grinding equipment. It was also shown that implementation of the split-feed HydroFloat™ circuit reduced the amount of fine material entering the existing conventional flotation circuit, as a result of the increased grind size and the multi-stage classification. In practice, this reduction in fines will likely provide a slight increase in recovery, as fewer ultra-fine particles (<20 microns) are present.

TAILINGS RETREATMENT

As an alternative and somewhat less disruptive approach, the combined flowsheet can also be applied for tailings retreatment. In this application, the primary objective is determine whether the proposed circuit can economically recover coarse (+150 micron) and ultra-fine (-15 micron) copper and molybdenum values that are currently lost to tailings. The flowsheet has been evaluated at pilot scale (5 tonne/hr) at several industrial sites. The rougher pilot-plant, shown in Figures 9 and 10, consisted of classification and flotation equipment that was designed based on data gathered from preliminary laboratory-scale testing.

Typical results from pilot-scale tests of this flowsheet are summarized in Table 1. As expected from the preliminary lab results, nearly 60 percent of the feed copper value reported to the classifier underflow, of which 35.8% (60% unit Cu recovery) was recovered in the HydroFloat™. Likewise, 20.5% (51% unit Cu recovery) of the feed copper values that reported to the fines fraction (classifying cyclone plus CrossFlow™ overflows) were recovered by the rougher StackCell™ circuit. The overall circuit produced a combined copper recovery of 56.2% at a grade of nearly 0.8% with a concentration ratio of 15. Additionally, 29.6 percent of the available molybdenum was also recovered. These results clearly illustrate that the combined coarse/fine flowsheet can recover a substantial portion of copper and molybdenum that is currently lost due to inefficiencies in the typical copper sulfide flowsheet.

Stream	Grade (%)		Recovery (%)	
	Cu	Mo	Cu	Mo
Feed	0.092	0.010	100.0	100.0
Fines Conc.	0.558	0.043	20.5	14.7
Coarse Conc.	1.008	0.045	35.8	14.9
Combined Conc.	0.779	0.044	56.3	29.6

Table 1
Product grade and recovery for pilot-scale tailings retreatment test program.

CONCLUSIONS

The split-feed flowsheet developed by Eriez was specifically engineered to extend the particle size range for sulfide flotation beyond what is achievable using current technology. The HydroFloat™ technology can recover coarse particles that were once considered too large to be upgraded by conventional froth flotation machines. Results show that particles as large as 850 microns containing as little as 1 percent surface expression of hydrophobic mineral can be recovered. Testing and simulation results demonstrate that incorporating this technology into an existing plant can potentially increase mill throughput by as much as 20-25 percent without adding additional comminution capacity.

In addition to the economic benefit of capacity expansion, there are significant indirect benefits associated with flotation of coarse sulfide values. The first is the ability to maintain a significant amount of the tailings sand at a coarse size. The coarse material is important for

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construction of tailings dams and provides better water drainage. This latter advantage is particularly important in many South American countries where fresh water is increasingly difficult to obtain. Also, the HydroFloat™ circuit offers the advantage of being able to recover acid-forming sulfide minerals such as pyrite at a very coarse size. Test results show that over 90 percent of the sulfur-bearing minerals can be recovered from the coarse fraction. Subsequent differential flotation of the pyrite allows for separate sequestration of the acid-forming minerals.

Likewise, test work has shown that the Eriez StackCell™ can efficiently extend the particle size range for fine sulfide recovery. The technology operates with a focused energy input which maximizes bubble/particle contacting, resulting in an extremely high flotation rate. As a result of the high kinetics, cell volume can be substantially reduced while achieving the same level of metallurgical performance. Pilot-scale test work conducted at various copper producing sites around the world confirms that comparable results can be achieved with less than half the energy and floor space required by conventional flotation machines.

Extensive testing of the Eriez hybrid flowsheet which combines both the HydroFloat™ and StackCell™ technologies has demonstrated that the classic "elephant curve" can be extended on both the coarse and fine end while also providing an increase in plant capacity and reduction in power and space requirements.

