RECOVERY OF VALUES FROM A PORPHORY COPPER TAILINGS STREAM

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ABSTRACT

The efficiency of the froth flotation process has long been known to be strongly dependent on particle size. For sulfide minerals, good recoveries are typically achieved in industrial flotation circuits for particles in the 30 to 150 μm size range. Particles outside this critical size 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. In response to these limitations, a series of experimental studies were conducted to determine whether particles previously lost as tailings could be economically recovered using a suite of novel flotation technologies developed for upgrading ultra-coarse and ultra-fine particles in the industrial minerals industry. For the case of ultra-coarse particles, a fluidized-bed flotation system called the HydroFloat™ separator was tested. The data obtained using this novel flotation device in both laboratory- and pilot-scale trials showed that good recovery of previously lost sulfide values up to 850 μm diameter could be achieved. Similarly, for ultrafine particles, a high-intensity cavitation-based column cell was tested. This technology, which utilizes high-shear contacting of slurry and gas, was capable of recovering valuable ultra-fine sulfide that were previously lost due to the low capture efficiency of conventional flotation processes. The objectives of this article are (i) to describe the unique operating principles of these two advanced flotation technologies and associated ancillary classification equipment, (ii) to present laboratory- and pilot-scale experimental test data showing the metallurgical benefits of the proposed novel flowsheet for sulfide tailings processing, and (iii) to provide a generic cost-benefit analysis of the proposed system for recovering lost values in existing sulfide tailing streams.

KEYWORDS

Tailings recovery, coarse particle flotation, fine particle flotation, HydroFloat™

INTRODUCTION

Improving the recovery of coarse (+150 µm) and ultrafine (-30 µm) particles in flotation has been a long-standing goal within the minerals processing industry. Research on the relationship between particle size and floatability began in the early 1930s in work presented by Gaudin et al. (1931) which showed that coarse and fine particles are more difficult to recover than intermediate size particles. This relationship is true for most minerals, although the optimum size range may change depending on the ore being processed. This finding is illustrated in Figure 1, which shows the flotation response of copper ore as a function of particle size using conventional flotation techniques. This finding has been confirmed through countless investigations showing that recovery is maximized between 30 and 150 µm. Inspection of Figure 1 shows that there is a distinct drop in recovery outside of this range when using conventional flotation techniques which results in a concentration of metals in the ultrafine and coarse tailings. This is illustrated from the deportment data that is plotted alongside the recovery data in Figure 1. This data was collected from operating plants where samples from the tailings stream were analyzed on a size-by-size basis. As shown, a significant amount of value still remains in the tailings in the finest and coarsest size fractions.

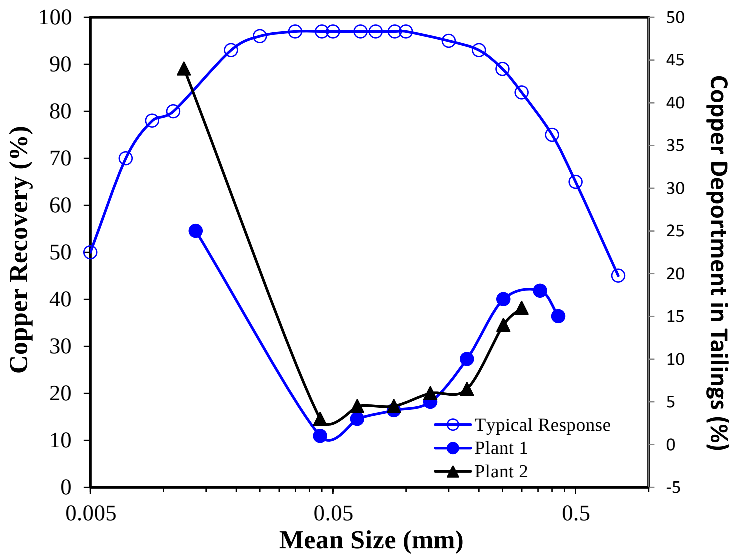

Figure 1 - Typical conventional flotation response and corresponding deportment of pay metals in tailings

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, as plants and equipment continue to grow in size, many of the capital savings achieved by utilizing fewer cells are lost due to inefficient mixing intensity. In contrast, the reduction in recovery for coarse particles is often attributed to detachment due to excessive turbulence within conventional mechanical flotation cells. According to Soto and Barbery (1991), these types of flotation cells operate with contradictory goals. A conventional cell needs to provide enough agitation to maintain all the particles in suspension, shear and disperse air bubbles, and promote bubble-particle collision. However, this approach is counterproductive for the recovery of coarse particles which requires a quiescent system for minimizing detachment. Data show that the maximum floatable particle size drops dramatically when conditions are turbulent, but can increase to several millimetres when conditions are quiescent (Schultz, 1984; Soto, 1988). 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 150 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.

The HydroFloat™ separator was specifically designed to address the aforementioned 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. Because of these unique features, the HydroFloat™ is able to recover particles with minimal surface expression. For example, Figure 2 shows +250 μm concentrate particles collected from a pilot-scale test 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 was still sufficient for these particles to be recovered using the HydroFloat™ separator.

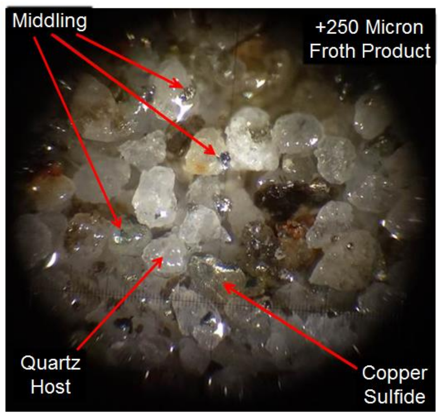

Figure 2 – Photo of middling particles recovered from tailings using the HydroFloat™ technology

Understanding that current industrial flotation practice is only amenable to recovering particles in a relatively narrow size range, it becomes obvious that another process or approach is required to achieve maximum return on each mining investment. As mining markets continue to get tighter and payback tougher to achieve, it becomes increasingly more important for mining companies to employ processes that maximize the recovery of valuable minerals from their ore reserves. By definition, this means that both ultrafine and coarse recovery must improve. As such, the Eriez Flotation Division has undertaken several laboratory- and pilot-scale test program to evaluate the feasibility of these novel flotation technologies for recovering lost metal values from current tailings.

EXPERIMENTAL

Several series of laboratory and pilot-scale tests were undertaken to demonstrate the effectiveness of the HydroFloat™ technology for recovering coarse particles from a sulfide tailings stream. The purpose of the laboratory work was to verify that the suggested equipment could achieve the desired separation results and provide a rough estimate of unit capacity. The subsequent pilot-scale work was conducted to confirm expected metallurgical performance and to evaluate the long-term reliability of the process.

Laboratory Testing

The laboratory work was undertaken using a semi-batch approach to classification and flotation. Testing was undertaken using a 500-kg bulk tailings sample collected from an operating copper plant in South America. The bulk sample was initially screened at 2 mm to remove tramp oversize. The minus 2 mm material was subsequently fed to a 200 cm^2 by 50-cm height continuous laboratory-scale CrossFlow™ fluidized-bed separator to produce a coarse/fine cut at ~125 μm. A hindered-, or fluidised-bed separator, is commonly used for particle classification. These devices are open-top vessels into which elutriation water is injected through distribution pipes that extend across the base of the cell. During operation, feed solids are introduced into the upper section of the separator and are permitted to settle. The upward flow of elutriation water creates a fluidized "teeter bed" of suspended particles. The small interstices within the bed create high interstitial liquid velocities that resist the penetration of the slow settling particles. As a result, fine particles accumulate in the upper section of the separator and are eventually carried over the top of the device into a collection launder. Coarse particles, which settle at a rate faster than the upward current of rising water, eventually pass through the fluidised bed and are discharged through one or more restricted ports in the bottom of the separator. The fines fraction from classification was subsequently conditioned in stirred-tank reactors and fed to continuous 7.5-cm diameter by 2-m tall CavTube™ laboratory column flotation cells arranged in a rougher/scavenger configuration. The CavTube™ column operates with an externally mounted dynamic sparging system. Slurry is withdrawn from the column base, aerated by means of the sparger, and returned to the column. This sparging technique has been shown to benefit the recovery of fine particles (Zhou et. al., 1994; Kohmuench et. al., 2012). The coarse (+125 μm) underflow from the CrossFlow™ was conditioned and fed to 15-cm diameter HydroFloat™ flotation cells assembled in a rougher/scavenger configuration. As shown in Figure 3, the HydroFloat™ consists of a circular tank subdivided into an upper separation chamber and a lower dewatering cone. The device operates much like a traditional hindered-bed separator; however, in this case, the teeter bed is continuously aerated by injecting air into the fluidization water. As the air bubbles rise through the teeter bed, they become attached to hydrophobic particles and rise to the top of the separation chamber. 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 and are discharged through the underflow nozzle. The fundamental operating principle of the HydroFloat™ cell has been fully discussed in the literature (Mankosa et al, 1999; Mankosa and Kohmuench, 2003; Kohmuench et al., 2007; 2010; 2013).

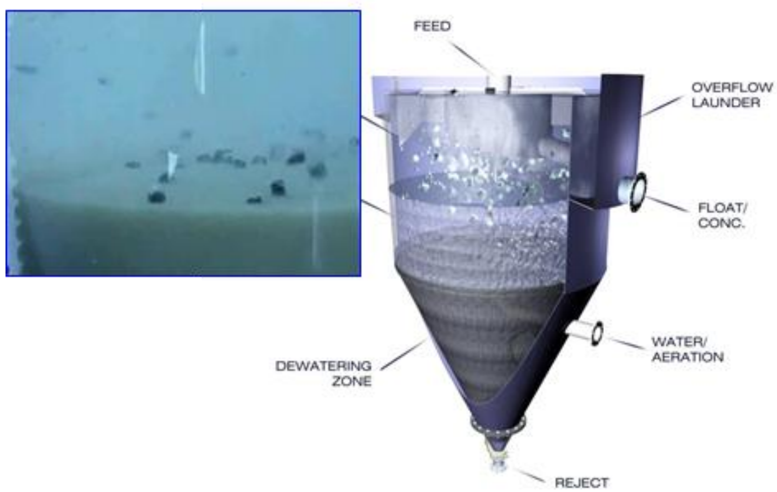

Figure 3 – Schematic illustration of HydroFloat™ separator

Pilot-Scale Testing

To further demonstrate the effectiveness of the HydroFloat™ separator for recovering lost copper values from tailings, a 5 tonne/hr pilot-plant was designed, constructed, installed and tested at an industrial concentrator site. The pilot-plant flowsheet, which is shown in Figure 4, consisted of classification and flotation equipment that was designed based on the data gathered from the initial laboratory-scale test program. During operation, 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 a 25-cm 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 cylone 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 cyclone overflow was combined with the CrossFlow™ overflow and directed to a conditioning tank. The conditioned 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 from the CrossFlow™ was conditioned and fed to a pair of 0.3-m diameter HydroFloat™ flotation cells. 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 (P_{80} = 80 µm). The ball mill discharge was combined with the fine concentrate from the column circuit and fed to conditioning tanks followed by cleaner flotation columns.

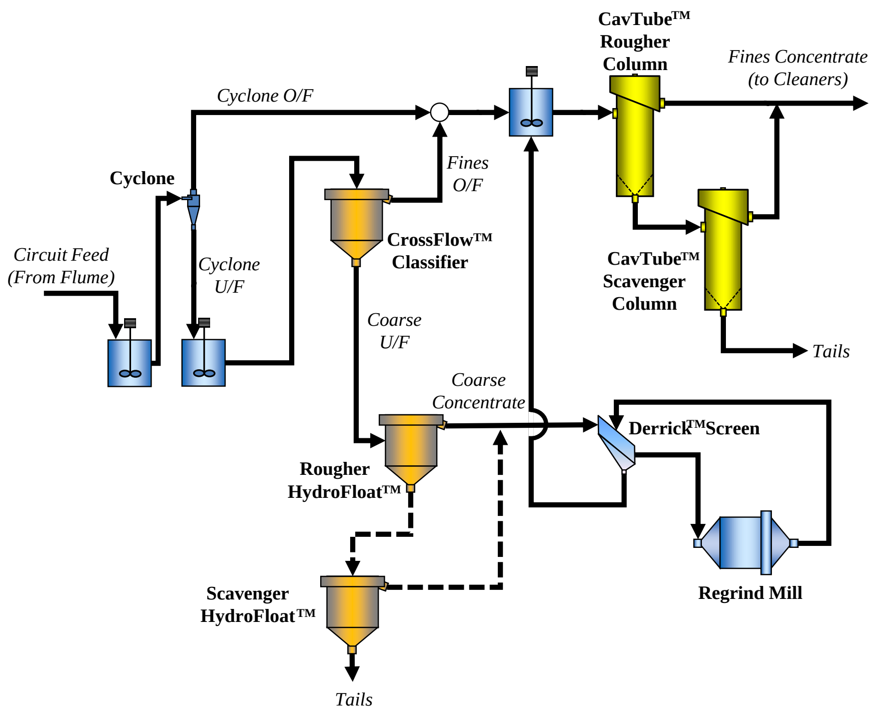

Figure 4 – Schematic diagram of pilot test circuit for copper sulfide tailings treatment

A parametric test program was established to evaluate the overall circuit performance for recovery of copper and molybdenum from the plant tailings stream. 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 sulfur. All results were mass balanced to properly assess the validity of each test sequence. The results from the test campaign are discussed in the following section.

EXPERIMENTAL RESULTS

Laboratory Testing

The initial test work for this project was conducted at laboratory-scale using a representative bulk sample collected from the main tailings discharge from an operating plant. The as-received sample was evaluated for particle size, copper and molybdenum content (by size) and compared to current operating results to ensure that a representative sample was collected. A comparison of the overall particle size distribution and copper content by size is presented in Figures 5 and 6. The as-received copper content ranged from 0.09-0.11% and the molybdenum content from 0.01-0.02%.

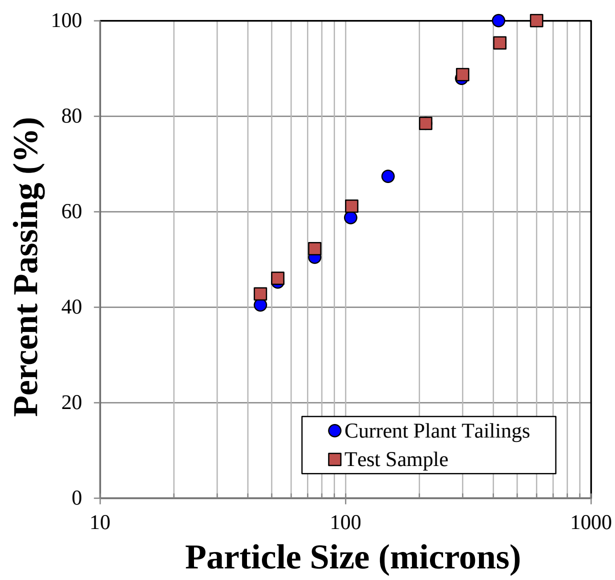

Figure 5. Particle size distribution for test sample and current production tailings

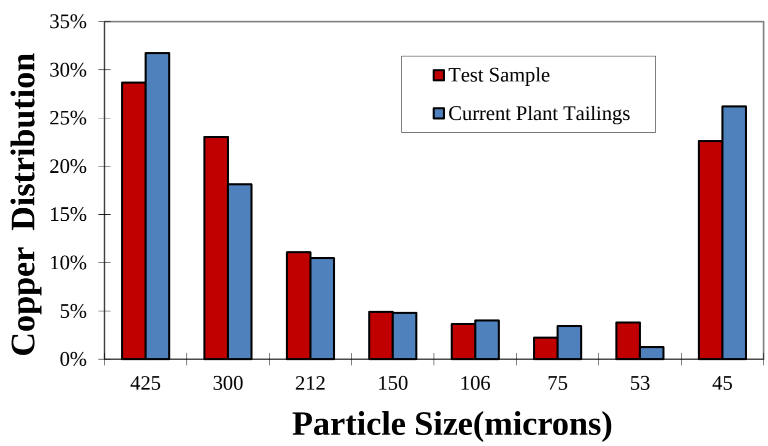

Figure 6. Copper distribution by size for plant and as-received samples

As described above, the first step in the laboratory-scale test program was to classify the as-received material into coarse and fine fractions using a laboratory CrossFlow™ hindered-bed separator. A cut-point (d_{50}) of 150 μm was targeted to ensure that the subsequent coarse particle flotation separator had the desired top-to-bottom particle size ratio. The results from this test are summarized in Table 1, which shows that ~77% of the mass reported to the classifier overflow along with the majority of the molybdenum (64.3%), while the bulk of the copper (59.3%) reported to the coarse underflow product.

Table 1 - Classification results from the laboratory test program

	Grade (%)			Distribution (%)		
	Feed	Overflow	Underflow	Feed	Overflow	Underflow
Mass	--	--	--	100.0	77.2	22.8
Cu	0.092	0.048	0.239	100.0	40.7	59.3
Mo	0.010	0.009	0.016	100.0	64.3	35.7
Fe	4.17	4.25	3.88	100.0	78.7	21.3
S	1.66	1.68	1.59	100.0	78.2	21.8

A rougher/scavenger column cell circuit was configured for testing the fines fraction (CrossFlow™ overflow). Numerous tests were conducted as a function of chemical addition rate, feed rate and column operating conditions. A typical data set is shown in Table 2. These results indicate that 46% copper recovery was achieved at a concentrate grade of 0.56% copper. Total mass recovery was less than 5% for the combined rougher/scavenger concentrate. An additional goal of this test program was to recover all sulfur-bearing minerals – predominantly pyrite. Selective recovery and concentration of pyrite allows for containment of these minerals, thereby significantly reducing the acid forming potential of the final tailings. The results in Table 2 show that nearly 90% of the sulfur-bearing minerals were captured in the combined concentrate.

Table 2 – Laboratory test results for fine flotation of copper tails

	Grade				Mass	Recovery (%)			
Stream	Cu	Fe	S	Mo	(%)	Cu	Fe	S	Mo
Feed	0.050	4.0	1.6	0.008	100.0	100.0	100.0	100.0	100.0
Rgh Conc.	0.570	33.1	37.1	0.093	3.7	42.2	31.1	85.8	43.0
Scav. Conc.	0.468	14.3	13.2	0.083	0.5	4.4	1.7	3.9	5.2
Combined	0.558	31.0	34.4	0.092	4.2	46.6	32.8	88.9	48.2

Coarse flotation tests were conducted using the underflow generated from the classification test work. As shown in Table 3, the coarse feed grade was ~0.2% copper and ~0.015% molybdenum. The HydroFloat™ feed contained material 46.7% coarser than 300 µm. Furthermore, the data show that the molybdenum and copper values are concentrated in the coarser size fractions. This was expected as the existing technology within the concentrator achieves good recoveries of -150 µm material, while suffering on the coarsest end.

Table 3 – Laboratory feed sample for coarse flotation

Size	Mass	Assays (%)			
(Microns)	(%)	Cu	Fe	S	Mo
+425	18.9	0.306	2.5	0.6	0.015
425 x 300	27.7	0.268	2.5	0.6	0.015
300 x 150	49.3	0.168	3.1	1.0	0.016
-150	4.1	0.109	23.0	15.6	0.014
Overall	100	0.219	3.6	1.4	0.015

A series of steady-state tests were conducted on the coarse tailings fraction. Initially, a rougher-scavenger circuit was utilized. Preliminary results, however, indicated that a rougher-only approach provided similar copper and molybdenum recovery. The overall results from this test work are provided in Figure 7, which shows that copper recoveries ranging from 60-65% can be achieved. In all cases, a high recovery of sulfur-bearing minerals was also achieved. Specifically, the molybdenum recovery ranged from 40-45%, while the sulfur recovery reached nearly 90%. Total weight recovery to concentrate ranged from 13-17%.

A microscopic view of the +425 micron concentrate and tailings is shown in Figure 8. In this case, no free sulfides were visible in the tailings sample generated by the HydroFloat™. Further inspection of the concentrate indicated that middlings and particles having very little exposed hydrophobic surfaces were being successfully recovered to the HydroFloat™ product. As a result of this visual inspection - and the fact that the coarsest tails fraction was still showing copper content in excess of 0.2% - it was assumed that the liberation in the coarsest fractions of this particular sample was insufficient to allow for efficient upgrading using a surface-based separation process.

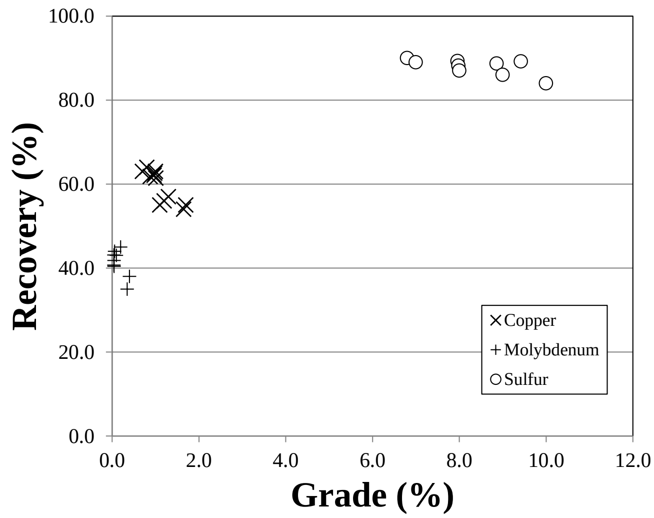

Figure 7. Laboratory results for coarse particle HydroFloat^{TM} flotation test work

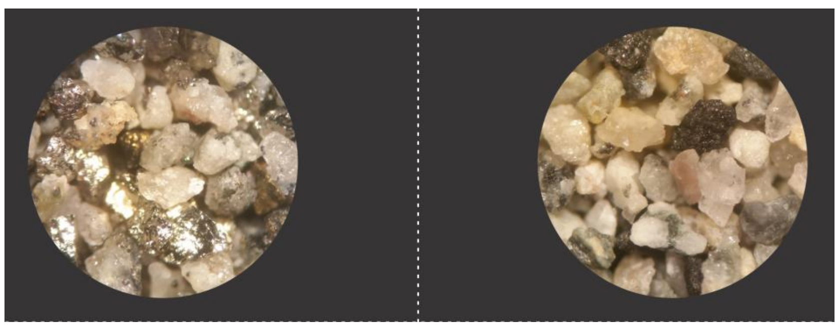

Figure 8 - Microscopic view of +425 concentrate (left) and tailings (right) particles

Pilot-Scale Testing

The primary objective of the test program outlined in this paper was to determine whether the proposed circuit is capable of economically recovering copper and molybdenum values that are currently lost to tailings at an industrial concentrator. An additional objective was to sequester acid-forming minerals such as pyrite so they can be separately isolated and contained for long-term disposal and treatment. The test results from the pilot-scale test program summarized in Table 4 show that both these goals were largely achieved. Similar to the lab results, ~60% of the feed copper value reported to the classifier underflow, of which 35.8% (60% unit Cu recovery) was recovered in the single-stage HydroFloat^{TM} flotation circuit. Likewise, 20.5% (51% unit Cu recovery) of the feed copper values that reported to the fines fraction (classifying cyclone plus CrossFlow^{TM} overflows) were recovered by the rougher/scavenger column 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. The results for sulfur and molybdenum are also included in Table 4. Sulfur floated with a high degree of recovery in both the fine and coarse circuits to provide an overall recovery of 88.2%. In addition, 29.6% of the available molybdenum was recovered. These results clearly illustrate that the combined coarse/fine flowsheet is capable of recovering a substantial portion of copper and molybdenum that is currently lost due to inefficiencies in the typical copper sulfide flowsheet; specifically recovering ultrafine (<25 μm) and coarse (>125 μm) material.

Table 4 - Summary of metallurgical results for sulfide recovery from tailings

Stream I.D.	Mass (%)	Grade (%) Cu	Grade (%) S	Grade (%) Mo	Distribution (%) Cu	Distribution (%) S	Distribution (%) Mo
Plant Feed	100	0.092	1.7	0.010	100.0	100.0	100.0
Fines Product	3.4	0.558	34.4	0.043	20.5	69.9	14.7
Coarse Product	3.3	1.008	9.3	0.045	35.8	18.3	14.9
Combined Product	6.7	0.779	22.1	0.044	56.3	88.2	29.6

DISCUSSION

Data collected in this study suggest that an additional 2100 kilograms of copper per day can be recovered from a 100,000 tpd concentrator using the proposed split-feed flowsheet. At the current copper price of USD $4.40/kg, this represents USD $200,000/day (USD $70 MM/year) of additional revenue. This does not include the benefit of additional molybdenum recovery or other associated pay metals. In addition to the increased metals value, the split-feed flowsheet offers several cost-saving advantages. The most significant is that the existing coarse material can be processed, and the metal values recovered, without further grinding. As presented above, ~23% of the tailings stream was coarser that 125 μm. The classic approach for sulfide processing requires that this material be ground to facilitate processing with conventional flotation cells. This traditional method would also require a significant outlay for capital equipment for the comminution circuit as well as on-going operating costs for consumables (media, liners and power) and maintenance. The proposed coarse processing alternative using the HydroFloat™ separator offers the advantage of reducing the associated grinding costs by nearly an order of magnitude.

Finally, there are two significant indirect benefits associated with successfully carrying out coarse flotation of sulfide values. The first is the ability to maintain most of the tailings sand at a coarse size. The coarse material is important for construction of tailings dams and, additionally, provides better water drainage. This latter advantage is particularly important in many South American countries where fresh water is increasingly difficult to obtain. The second indirect benefit, as mentioned earlier, is that the HydroFloat™ circuit offers the advantage of being able to recover acid-forming sulfide minerals such as pyrite at a very coarse size. This capability is clearly demonstrated by the combined product sulfur recovery of nearly 90% in the pilot-scale test program as shown previously in Table 4.

Another advantage of the HydroFloat™ circuit identified during the pilot-scale test program was the ability of the technology to operate in a stable and consistent manner in a plant environment even with highly variable tailings slurry as the feed stream. This final point is supported by the data shown in Figure 9, which illustrates the copper grade and recovery achieved during a long-term (4 day) plant test. 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 future publications.

SUMMARY

A novel split-feed flowsheet for copper sulfide tailings recovery has been demonstrated at a pilot-scale in an operating plant environment. The flowsheet was designed specifically for the recovery of very fine and very coarse particles that have traditionally been lost in conventional processing circuits. The flowsheet utilized a two-stage, high-efficiency classification circuit to generate a “slimes-free” ultra-coarse stream and a “sands-free” ultra-fine stream. Hydrophobic particles in the ultra-fine stream were efficiently upgraded using CavTube™ column flotation cells. Sulfides present in the ultra-coarse stream were efficiently recovered using a new hybrid flotation technology known as the HydroFloat™ separator. Data obtained using this novel separator indicated that good recoveries of previously lost sulfide values up to 850 μm diameter could be achieved in an industrial concentrator. Preliminary economic calculations suggest that substantial gains can be achieved using this twin-circuit flowsheet to treat tailings streams currently discarded by the sulfide minerals industry.

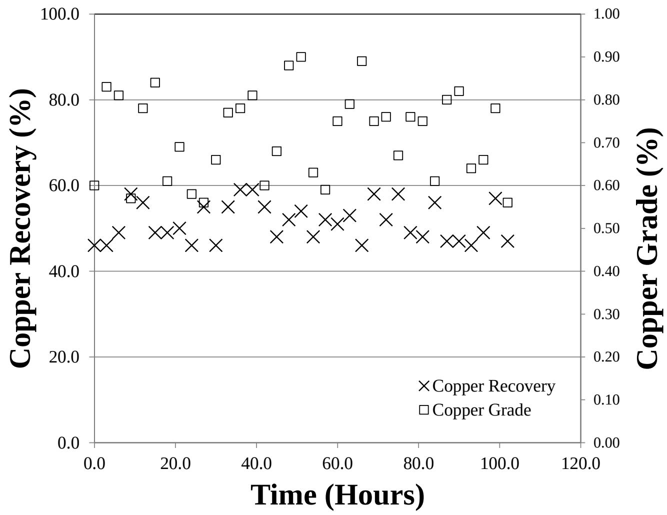

Figure 9 – Long-term pilot circuit test

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