A COMPARISON OF TWO CIRCUIT APPLICATIONS FOR IMPLEMENTATION OF COARSE PARTICLE FLOTATION

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ABSTRACT

The use of fluidized beds to enhance the flotation efficiency of coarse particles has been practised industrially using Eriez' HydroFloat® separator in phosphate and potash for many years and has recently been successfully extended to sulfide minerals. This promising technology will recover "lost" coarse metal units, which can be 5-10% of the metal units contained in the mill feed.

In the "tailings scavenging" operating philosophy, the HydroFloat® will enhance production revenues with a small increase to capital and operating costs. This application allows the feed to the mill circuit to be incrementally increased, with an increase in the average particle size reporting to the flotation circuit, using the HydroFloat as a "back-stop." Although highly profitable, this configuration does not enable other "green" benefits, such as reductions in energy, conventional flotation capacity, water consumption and the amount of final waste stored in conventional tailing facilities. These additional benefits are possible by considering a "coarse gangue rejection" operating philosophy.

Where is the best flowsheet location to add a coarse particle flotation (CPF) unit, and what will a CPF optimized flow-sheet look like? In this paper we will generically consider both of these questions. To illustrate, we will present test-work and standard mineral processing calculations to show the benefits of two different CPF installations taking advantage of the same ore body and mill product.

INTRODUCTION

It is a challenging time to be in the resources extraction industry. World-class high- grade deposits are disappearing, resulting in lower grade deposits that require larger amounts of energy and earth moving. Simultaneously, miners are under intense scrutiny to deliver their products to environmentally aware consumers at commodity prices while maintaining a smaller "environmental footprint," and that is typically short-hand for less consumption of green house gas (GHG) emitting energy sources and water. Public companies are increasingly lobbied by non-governmental organizations (NGOs), governments, community stakeholders and shareholders to become more innovative in reducing their environmental footprint. At the same time, more people are entering the global middle class every year, increasing the worldwide demand for mined commodities such as metals and fertilizers (Kharas and Hamel, 2018). It is in this context that many are investigating disruptive ways to adapt the mining process and reduce its environmental footprint.

The most energy intensive component of the mining process is crushing and grinding, which is required to reduce the size of ore from boulders to the size range, about 200 microns or less for most copper sulfide ores, where it can practically be floated using conventional technology. Most of the water used in mining is required to carry and convey fine ore particles through the process. Coarse particle flotation (referred to throughout this paper as CPF) is an innovative approach, based on Eriez' HydroFloat® technology, which enables semi-liberated ore to be floated at much coarser sizes, typically up to 600 microns for many copper sulfide ores. This technology has been shown to be scaleable and industrially robust, with mining companies, engineering companies, and consultants beginning to study ways to use the HydroFloat in CPF. Many people have become interested in understanding the best place to apply this new technology in mineral processing flow-sheets. In this paper, we will consider two different configurations of CPF using case studies developed from a single operation, Capstone's Cozamin mine in Zacatecas.

Conventional stirred tank cells are the primary unit operation used in more than 90% of mineral processing flotation operations worldwide. This is despite their inherent inefficiency outside of a narrow range of optimal particle size. The mechanism for flotation losses with coarse ore particles has been reported (Falatsu, 1989) and is well accepted, but has not been addressed by conventional flotation equipment manufacturers. For example, audits of two world class copper producers have shown 35-60% of copper and molybdenum in final tailing streams reside in the size class greater than 150 microns (Wasmund, 2019). Over the last ten years there has been increased interest and product development in the area of CPF for sulfide minerals, using liquid fluidized beds to host the flotation process, as practised in the Eriez HydroFloat. The design features and fundamental principles that make the HydroFloat successful have been explained elsewhere (Mankosa, 2016). Applications are being demonstrated and commercialized, most notably, the HydroFloat as a tail scavenger at Newcrest's Cadia copper/gold concentrator in New South Wales (Vollert, 2019). In the "tail scavenging" (TS) application of CPF, the cost to build a stand-alone coarse particle flotation plant on the back end of the concentrator is justified by increasing the overall recovery of pay metals, and offering the possibility to increase plant capacity. This is the most obvious and natural first generation of HydroFloat installations, where a modest investment of capital for a stand-alone CPF plant can allow the capture of more than 50% of pay-metals in coarse mine tailings.

The second generation of applications for CPF involves tighter integration of the HydroFloat into the concentrator flow-sheet. This means that the entire plant becomes dependent on the performance and operability of the HydroFloat, but many additional benefits become available. The HydroFloat in the milling circuit can be used to produce a low grade concentrate and reject a coarse barren fraction of the mill output at a size between 200 and 700 microns. In the application known as coarse gangue rejection (CGR), the coarse tail is extracted near the beginning of the flow-sheet, akin to an ore sorting strategy. A significant reduction in the amount of grinding energy and size of the concentrator will be possible as well as a reduction in the amount of water that is required, since coarse tailing sand is easy to de-water and does not require impoundment in the same manner as fine tailings.

EXPERIMENTAL

Cozamin is a polymetallic sulfide mine, with pay-metals of copper, zinc, lead and silver, located in Zacatecas, Mexico and operated by Capstone Mining Corporation. The mill processes 3800 tonnes/per day, which is crushed in two stages and split between two parallel 12 foot diameter x 14 foot length ball mills, each receiving about 80 tonnes of fresh solids feed per hour and consuming about 800 kW of power. Both mill lines recombine and feed two parallel flash flotation cells, followed by conventional rougher flotation and then a flowsheet with re-grinding of rougher concentrate and selective flotation and production of separate copper, lead and zinc concentrates. The rougher recoveries for the main pay-metals of copper, zinc, lead and silver are 95%, 70%, 50% and 80% respectively. The final tail of this plant has a particle size of mostly less than 230 microns and is thickened and pumped to a conventional tailing impoundment at 55% solids by weight.

To evaluate the TS and CGR applications using the same ore body and mine, two 50 kg samples were taken from the Cozamin flow-sheet in 2016; one from the final tail and the other from the ball mill cyclone underflow. The cumulative particle size distributions are shown in Figure 1. Samples from each location were prepared and floated using an Eriez 150 mm diameter lab HydroFloat unit. The Eriez HydroFloat uses a fully developed steady state liquid fluidized bed, which requires some limit to the polydispersity or range of feed size distribution. For this reason, any CPF plant based on the HydroFloat technology will involve some size classification of the feed. In this test-work, the fines below 160 micron and the coarse component above 700 microns were removed, using two stages of screen classification. The pass-band material (+160 micron/-700 micron) was fed to the HydroFloat. In commercial applications, HydroFloat feed preparation can utilize cyclones, screens, the Eriez CrossFlow hydro-sizer, or any combination of these conventional classification technologies.

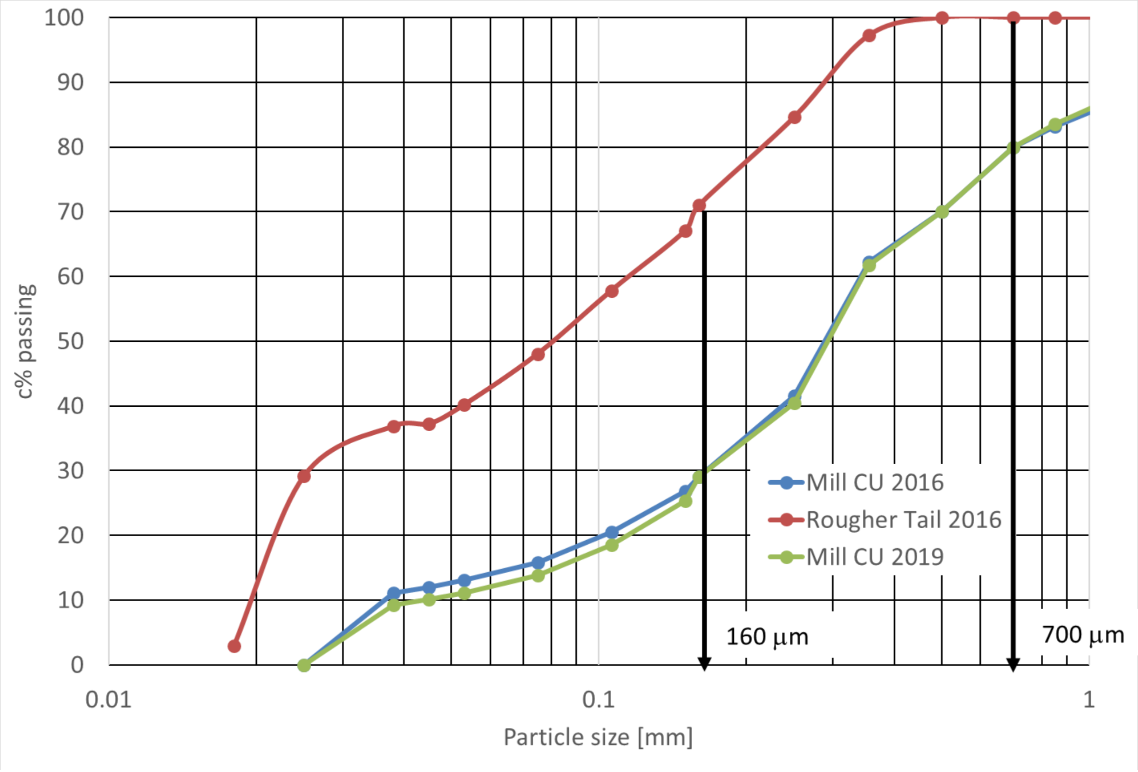


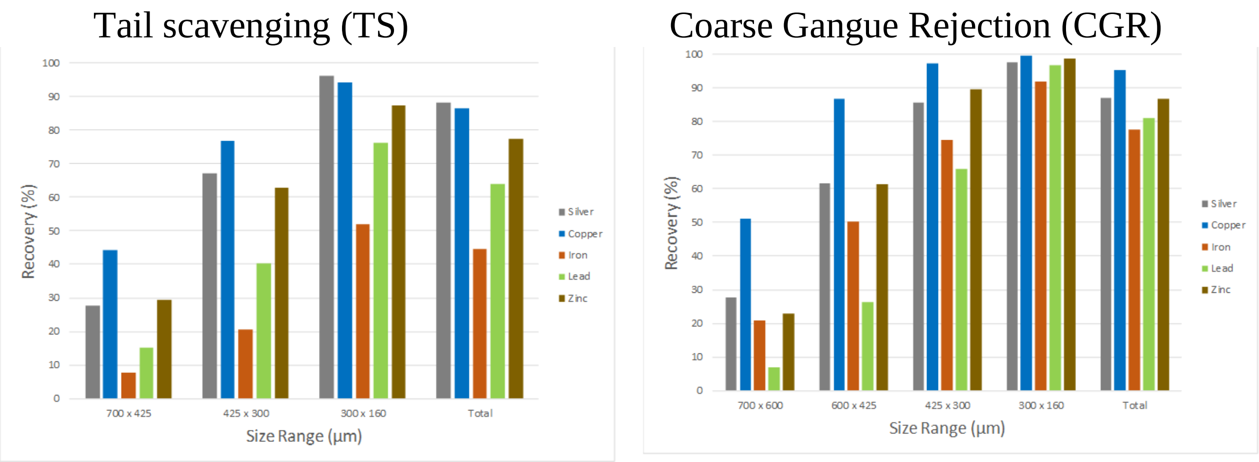
Figure 1: Cumulative size distribution of the rougher (final) tail and mill cyclone underflow samples used as the basis to evaluate the TS and CGR coarse particle flotation applications. The vertical tie-lines at 160 and 700 microns show where material was screened to prepare the HydroFloat feed.

Applying the two stages of screening, each sample was split into three size classes; minus 160 microns, 700 x 160 microns (HydroFloat feed), and plus 700 microns. The corresponding mass splits to each size fraction for TS and CGR applications are shown in Table 1. The third column indicates the mass fraction of the total feed that is suitable for flotation in the HydroFloat.

The HydroFloat flotation recoveries by size for the major pay-metals are illustrated as Figure 2 while the overall HydroFloat metal recoveries are shown in Table 2. In Table 3, the 80th percentile of the particle size distribution (d_{80}) is used to characterize the degree of coarseness of each sample.

Table 1. HydroFloat feed preparation and mass splits

Flotation sample	Percent of -160 micron removed [% of unscreened feed]	Percent of +700 microns removed [% of unscreened feed]	Percent of feed remaining after 2-stage screening -this is the HydroFloat feed [% of unscreened feed]
CGR (Mill CU)	30%	20%	50%
TS (Final Tail)	70%	0%	30%


Tail scavenging (TS)

Coarse Gangue Rejection (CGR)

Figure 2. Test-work recovery by size for silver, copper, iron, lead and zinc for the TS and CGR samples.

Table 2. Overall HydroFloat pay-metal recoveries

Flotation sample	Copper (%)	Lead (%)	Zinc (%)	Silver (%)
CGR (Mill CU)	95.0-95.3	80.9-90.0	85.0-86.8	87.0-90.0
TS (Final Tail)	86.4	63.9	77.4	88.3

Table 3. HydroFloat feed and tail size and mass splits

Flotation sample	d_{80} HydroFloat feed (µm)	d_{80} HydroFloat tail (µm)	HydroFloat Mass pull (wgt %)
CGR (Mill CU)	500	560	30.9
TS (Final Tail)	330	375	9.4

The TS results show a significant incremental recovery of metal units that are lost to final tailings using conventional flotation methods. Conversely, the CGR results show recoveries of all pay-metals are comparable to conventional flotation, but at vastly increased particle sizes.

RESULTS

There are a number of opportunities to study how the CGR results can be used to optimize the conventional mill circuit shown in Figure 3. As an example of this concept, two-stage screening of the ball mill cyclone underflow stream could be introduced as a way to scale up the experimental CGR results presented in the previous section of this paper. In this configuration, the minus 160 micron screen undersize, which is often misplaced in the cyclone underflow, is sent to conventional flotation, while the coarse plus 700 micron fraction is returned to the mill, which will reduce the mass but increase the size of returning ore. The 700 x 160 micron pass-band ore could be fed to the HydroFloat. As indicated by the flotation results summarized in Table 2 and Figure 2, treatment of this fraction via HydroFloat could produce a bulk float concentrate with comparable recoveries to the conventional circuit. This hypothetical flowsheet is shown as Figure 4. With a CGR circuit installed, a significant portion of the final plant tailing stream can be produced as a coarse final tail with a d_{80} particle size of more than 500 microns, with the remaining portion being produced as a fine final tail with a d_{80} particle size of approximately 200 microns.

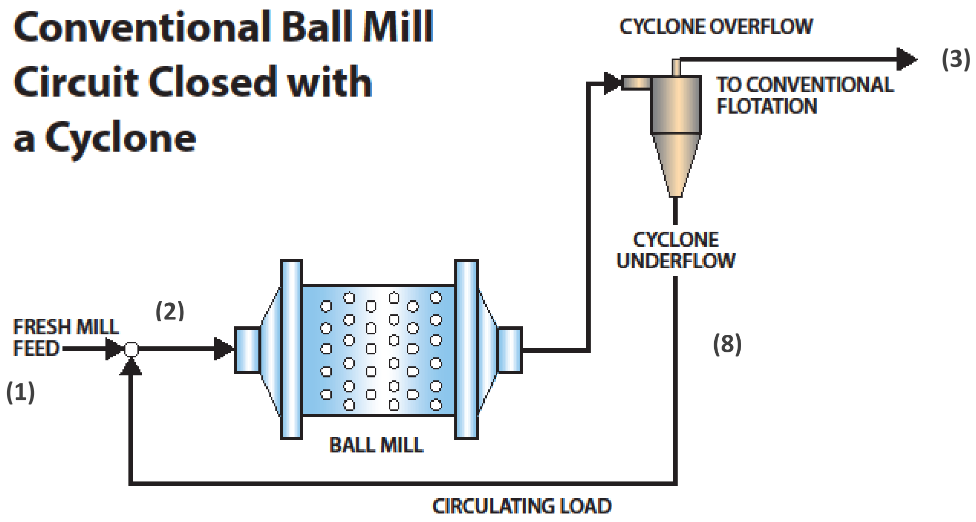


Figure 3: Conventional closed ball mill circuit with circulating load

To quantitatively evaluate the effect of the CGR flowsheet configuration on power consumption and the production of coarse and fine tails for the same mill capacity, a JKSimMet model was built and calibrated against the plant data from the mill circuit shown in Figure 3. Two models were run; one as shown in Figure 3 and one as shown in Figure 4. In both cases, the milling circuits received the same amount of fresh feed. JKSimMet is a steady state process modelling software which has models for standard mineral processing unit operations. This package allows each solid stream to be modelled as a family of size classes and the equations of continuity are solved for total mass as well as size using a population balance approach. The conventional milling circuit shown in Figure 3 was modeled using ball mill and cyclone models as the primary unit operations. Conversely, modeling of the CGR circuit incorporated the addition of two screening stages and a HydroFloat.

The ensuing mass flowrates for the Figure 3 (conventional) and Figure 4 (CGR) milling circuits are shown in Table 4. In addition, the change in power and proportion of fine and coarse final tail for both circuit options are shown in Table 4.

Table 4: Comparison of the CGR simulation with the current mill circuit (base-case)

Mass flowrate [t/hr]	Conventional Circuit [Figure 3]*	CGR Circuit [Figure 4]**
1. Fresh mill feed	80	80
2. Total mill feed	230	121
3. Cyclone overflow	80	33
4. Total flow to conventional flotation	80	47
5. Cyclone Underflow	150	87
6. Minus 160 micron screen product	--	14
7. Plus 160/ minus 700 micron screen product	--	32
8. Return to circulating load	150	41
9. HydroFloat concentrate	--	9
10. HydroFloat coarse barren tail	--	23

*Plant audit, Sept 2019

** CGR JKSimMet simulation

Table 5: Comparison of the CGR simulation with the current mill circuit (base-case)

Mill circuit configuration	Power [kW]	Circulating Load [%]	d_{80} of ball mill output [µm]	Final tail that is fine [% of total]
Base-case (Figure 3)	800	186%	550	100%
CGR (Figure 4)	400	50%	1,200	30%

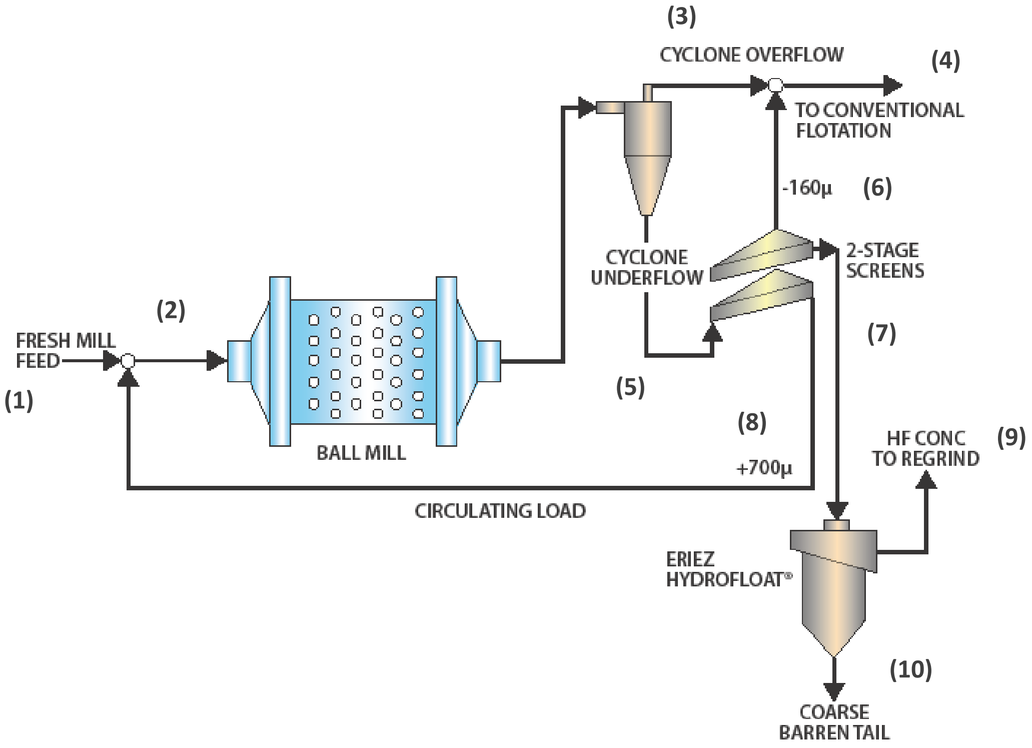


Figure 4: Hypothetical mill circuit reconfiguration to allow the CGR concept to be practiced

DISCUSSION

Effect on additional metal recovery

In the TS application, the main benefit is the additional metal units that can be obtained by scavenging final tails. For this analysis, we will assume that the HydroFloat concentrate can be upgraded using conventional regrinding and cleaning, and that additional cleaner capacity would be available in the existing plant. Further, we will assume that the metal contained in the plus 160 micron tails material comprises 50% of the total metal distribution within the tail. Combining this estimate with the results of Table 2, the incremental increase in rougher recovery by scavenging tails, along with the base-case, is shown in Table 6.

These results provide the initial estimate of incremental revenue associated with a TS business case. It is possible that throughput to the mill could be increased without losing recovery by increasing the plant mass throughput, which would “coarsen” the grind size of the feed to the ball mill, using the HydroFloat as a back-stop after conventional flotation, but this strategy has not been quantified here.

Table 6: Estimate of improvements in global rougher recovery with TS application

Circuit	Cu [%]	Zn [%]	Pb [%]	Ag [%]
Base-case	95	70	50	80
Incremental increase in base-case with TS	+2	+11	+16	+9

In the CGR application, it is difficult to predict any improvements in mineral recoveries. The addition of the CGR circuit in Figure 4 was assumed to have a neutral impact on overall recoveries if the HydroFloat recoveries were the same as the conventional bulk rougher circuit. However, this does not consider the benefit of diverting misplaced minus 106 micron ore away from the circulating load. The addition of fines (slimes) back into the circulating load will create over-grinding and potentially lower efficiency in flotation. As such, it is plausible that the two-stage screening process in Figure 4 would improve the recovery of the conventional flotation circuit, but no attempt has been made to quantify this. It is also possible that the CGR application could facilitate an increase in overall plant throughput, but this has also not been considered quantitatively in this analysis.

Effect on relative proportions of coarse and fine tailing produced

Using a conventional grinding circuit, the d_{80} of the final tail will be approximately 230 microns by measurement (Figure 1). For the Cozamin mill, this means that approximately 3,500 tonnes per day of the plant tail will exist in a slurry comprised of gangue particles substantially finer than 230 microns.

In the case of the TS application, some size classification operations would be required to prepare the conventional plant tail for treatment by the HydroFloat. Using the results in Tables 1 and 3, we can estimate that approximately 27% of the total tailing stream could be coarsened to a d_{80} of approximately 375 microns, but the remaining tail would be fine, with a d_{80} somewhere below 230 microns. This would achieve a comparable amount of particle size coarsening as sand cycloning, which is practiced at many sites.

In the case of the CGR flowsheet, practised as shown in Figure 4, approximately 23 tonnes/hr of a coarse barren tail would be permanently withdrawn from the ball mill return loop, as shown in Table 4. The d_{80} of this coarse barren tail from the simulation would be greater than 600 microns. The total corresponding amount of material going to conventional flotation, including the HydroFloat concentrate after regrinding, would be approximately 56 tonne/hr. This means approximately 30% of the total plant tail could be extracted at a size of greater than 600 microns. This will have a significant impact on mill sizing and power, conventional flotation capacity requirements, and options for impounding tails and recovering water, which are discussed next.

Impact on water consumption, impoundable tailings

The introduction of the TS application only creates a modest improvement to water and tailings handling and is comparable to the results achieved with the standard practice of sand cycloning.

For the CGR application, the biggest impact is the production of 30% of the total tailing stream as a coarse tail with a d_{80} size of greater than 600 microns. It would likely have non-plastic rheological properties, high hydraulic conductivity and would not have to be placed in a conventional tailing storage facility. It could potentially be used as borrow material to raise the dam or be mixed with finer material to be co-deposited. Moreover, it would reduce pumping and placement costs and space in the impoundment by 30%.

For our analysis, the costs for pumping water and placing thickened tailings in a conventional tailing facility are taken from Klohn Crippen Berger's "Study of Tailings Management Technologies" (Klohn Crippen Berger, 2017). This study indicates a typical cost to transport thickened tailings of \$0.20/tonne and \$1/tonne for long-term dam maintenance and water management. These represent typical costs in Canada and will be used for benchmarking purposes in the present study, keeping in mind that they could be much higher in regions where water is in short supply, such as Chile. It is assumed that the production of coarse sand would not require significant disposal or storage costs. With these numbers, the total costs to pump and store the Cozamin tailing stream would be approximately \$1.5 million per year which could be reduced by about \$440,000 per year with the removal of a coarse tail. This estimate of cost reduction does not include any additional savings that could be realized by reducing or eliminating the amount of fresh make-up water that is required seasonally at some facilities.

Impact on conventional flotation capacity

According to the simulation results of Table 4, the CGR application would also allow a reduction in conventional flotation capacity from about 80 tonnes/hr to 47 tonnes/hr, a reduction of approximately 40% from the base-case or the TS application.

Impact on mill power and sizing implications

These preliminary simulation results indicate that the CGR flowsheet, shown in Figure 4 can have a major impact on the mass flowrate in the circulating load and the grinding requirements compared with the base-case of Figure 3. The biggest effect is the total mass flow that is diverted away from the circulating load with the CGR approach and therefore a reduction in the total amount of material being milled. The work associated with the grinding is also less because the end-point of the grinding can be significantly coarser in the CGR application, as shown in Figure 5, where the output particle size of the mill unit can be increased from 550 to 1,200 microns and the mill circuit product P_{80} (summation of conventional flotation feed and HydroFloat feed) coarsens to 380 microns, compared with about 200 microns for the base-case. The reduced mass load and coarser circuit product yields a 50% ball mill power reduction in simulation. However, because the model data and simulation are based on closed circuit grinding, the estimate may be optimistic. This is because the highly reduced circulating load in the CGR circuit, make it more akin to open circuit grinding. For a conservative estimate of power reduction, the Bond-Rowland open circuit ball mill power relation (with no additional efficiency factors applied) is used to estimate the power required to reduce the feed size to the coarser CGR P_{80} in open circuit. This resulted in a more modest 29% power reduction. A partial explanation for the difference between the simulation and Bond-Rowland estimate may be that the efficiency provided by cycloning and screening in the CGR circuit are not reflected in the Bond-Rowland open circuit estimate (Rowland, 1972). Additional effort in future testing and modelling should be invested in testing the accuracy of these models for lower circulating loads. But at this level of accuracy , and assuming the conservative reduction in grinding power of approximately 232 kW and a price of \$0.15/kWh, this would create a power saving of approximately \$280,000 per year per mill at this facility or a total of \$560,000 per year.

With the de-rating of the ball mill and conventional flotation capacity just discussed, another possible application of CGR for a brownfield site would be to coarsen the grind of the ball mill feed and increase mass throughput to the plant with the remaining downstream unit operations essentially unchanged. This strategy has not been quantified by simulation here, but will be the subject of a future paper.

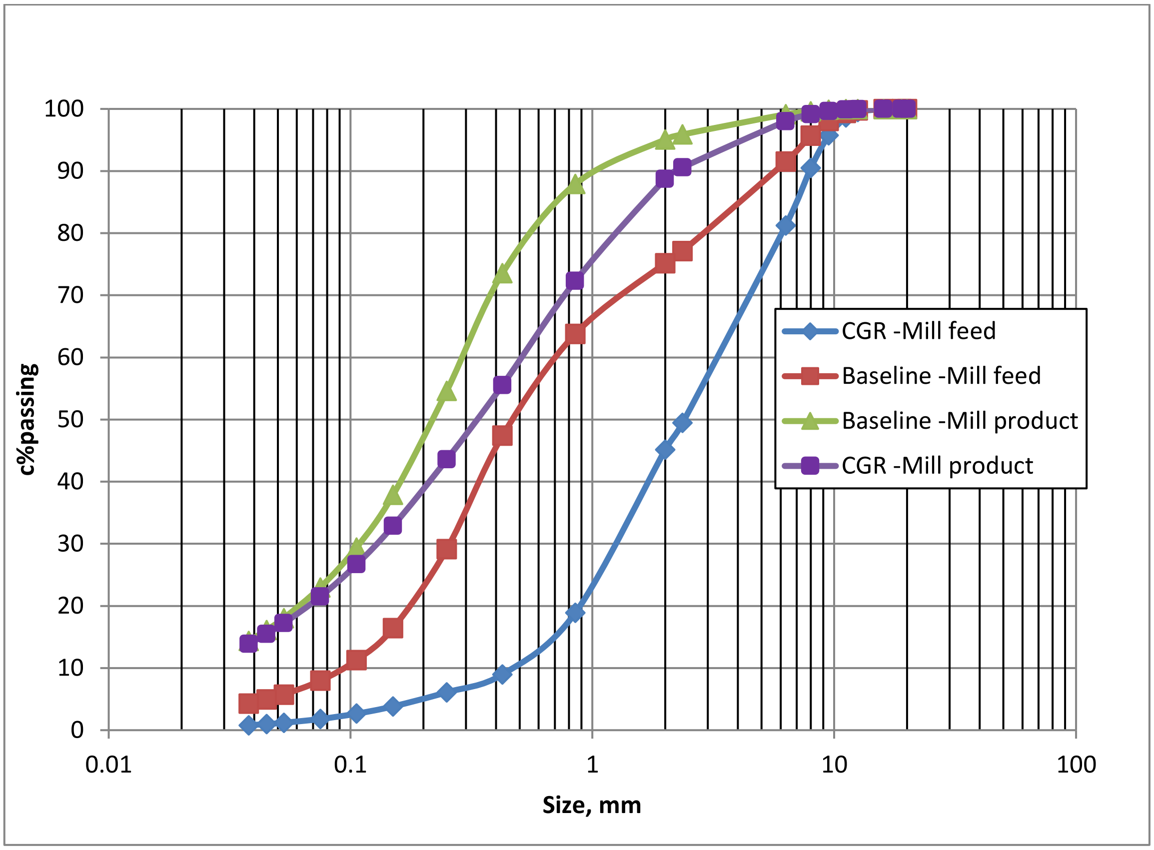


Figure 5: Simulation results of ball mill input and output size distributions for the base-case and CGR application

SUMMARY AND CONCLUSIONS

The results of this study have been combined in Table 7. Comparing with the base-case, the main quantifiable benefits of the TS option are in the capture of additional metal units. The classification required for the HydroFloat process will allow some tailing size classification, which would be comparable to conventional sand cycloning. Optionally, there may be the possibility to increase plant throughput, but this is difficult to quantify a priori since it requires knowledge of the dynamic interaction between comminution, conventional flotation and HydroFloat flotation.

Table 7: Estimates of the benefits of TS and CGR CPF configurations at Capstone's Cozamin

Circuit	Increase in plant recovery [%}	Reduction in ball mill power [%]	Reduction in float capacity [%]	Reduction in impoundable fine tail/ water [%]
Base-case	--	--	--	--
Base-case with TS	See Table 6	--	--	?
CGR	?	>29*-50%**	>40%**	>30%**

*Bond-Rowland open circuit estimate
**JKSimMet simulation

In the case of the CGR application, there is the possibility of an increase in overall recovery, but this cannot be quantified at this level of study. A combination of experimental and simulation results indicate that placing the HydroFloat in the mill circuit would result in a significant decrease in the mill load, resulting in a power decrease of 29-50%, and that approximately 30% of the total run of mine mill feed could be removed from the circuit prior to conventional flotation, resulting in a decrease of conventional flotation capacity by 40% and reduction in tailing management costs of 30%. Some typical North American numbers were provided to show the financial benefits of these improvements. At sites that are more remote, or where water is scarce, these results could be even more significant.

As stated in the discussion section, another possible opportunity with the CGR configuration in brownfield installations would be to increase the mass flowrate through the entire circuit (also known as "pushing tonnes") by changing the screen size on the screens that close the upstream crusher or SAG circuit. This would coarsen the ball mill feed and increase the grinding energy and conventional flotation requirements, which have been conveniently de-rated by CGR as shown Table 7. This would allow an inexpensive increase in plant capacity using CGR, although that benefit has not been simulated or quantified in this study.

The HydroFloat CPF technology creates new possibilities for extraction companies and engineers to renew their social contract with society by improving the efficiency and minimizing the detrimental impact of mining. This case study shows two possibilities for the HydroFloat unit operation to dramatically reduce energy, impoundable tailings, water and plant requirements.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Capstone Mining Corp. for providing access to process data from the Cozamin site and to Tony Lipiec of Fluor Canada for reviewing this paper and providing valuable insights.

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