Increasing Copper Recovery at Hudbay Minerals' Flin Flon Concentrator Operation

*J. Qiu[1], B. Lumsden[2], T. Boyd[1] and K. McTaggart[1]

[1]Hudbay Minerals, Manitoba Business Unit
Flin Flon Concentrator
1 Company Road
Flin Flon, Manitoba,
Canada R8A 1N9

[2]Ausmetec Pty Ltd
47/176 South Creek Rd
Cromer, NSW, 2099
Australia
*(*Corresponding author: barrylumsden@ausmetec.com.au)*

ABSTRACT

Hudbay Minerals' Flin Flon process plant produces a copper concentrate and zinc concentrate from the three ores it processes: 777, Reed and Lalor. Unlike many Cu-Zn ores, the average Zn: Cu ratio in feed is around 2:1, whereas, in many Cu-Zn separation plants the Zn: Cu feed grade is substantially higher than 2:1. The lower Zn: Cu in plant feed is a challenge for limiting Zn recovery to the Cu concentrate. While total recoveries of Cu and Zn at Flin Flon are very good; selectivity is the key challenge and small changes in ore or plant, can result in quite variable Zn recovery to Cu concentrate, and accordingly, Zn recovery to Zn concentrate.

Magnetic conditioning has been shown to be selective between the two paramagnetic minerals chalcopyrite and sphalerite. Statistical testing of magnetic conditioning was undertaken at Flin Flon with the objective of increasing Cu recovery to Cu concentrate without increasing the Zn recovery to Cu concentrate - in effect increasing Cu-Zn selectivity. This has been achieved elsewhere with magnetic conditioning with the probable mechanism being an increase in fine chalcopyrite recovery, and a reduction in entrained, ultrafine, non-activated sphalerite to Cu concentrate.

The results did indeed show an increase in Cu recovery to Cu concentrate of 0.8% to high confidence, but the decrease in Zn recovery to Cu concentrate was not to high confidence. This is effectively an increase in Cu: Zn selectivity in the Cu circuit – higher Cu recovery with no change in Zn recovery. However, while there was an increase of 1% in Zn recovery to Zn concentrate with magnetic conditioning, the variability in this parameter meant that this increase, though larger in magnitude than the Cu result, was not to high confidence.

KEYWORDS

Paramagnetic, magnetic, t-test, flotation, recovery

INTRODUCTION

Flin Flon Concentrator and Ore

Hudbay Mineral's Flin Flon concentrator, located in northern Manitoba was originally commissioned in 1930. The Flin Flon concentrator had a 1.45 mt/y capacity in 1999 and was expanded in two stages to reach a 2.18 mt/y capacity in 2004. This was to accommodate the increased production from the Konuto Lake and 777 Mine. Currently, the concentrator processes massive copper and zinc sulphide ores from 777 Mine, Reed Mine and Lalor Mine. The produced copper concentrate is sold to market while the zinc concentrate is forwarded to the company owned Zn Plant for high grade zinc production.

The feed ore is delivered into a two-stage crushing plant and crushed down to -1.25 inch prior to transferring to dedicated fine ore bins. The crushed fine ore is then milled in a pair of parallel rod mills followed by cyclone classification and ball mill regrinding. The cyclone overflow is directed to a conditioning tank, in which the flotation feed slurry was conditioned using a system of magnetic conditioners as well as pH elevation and reagent dosing.

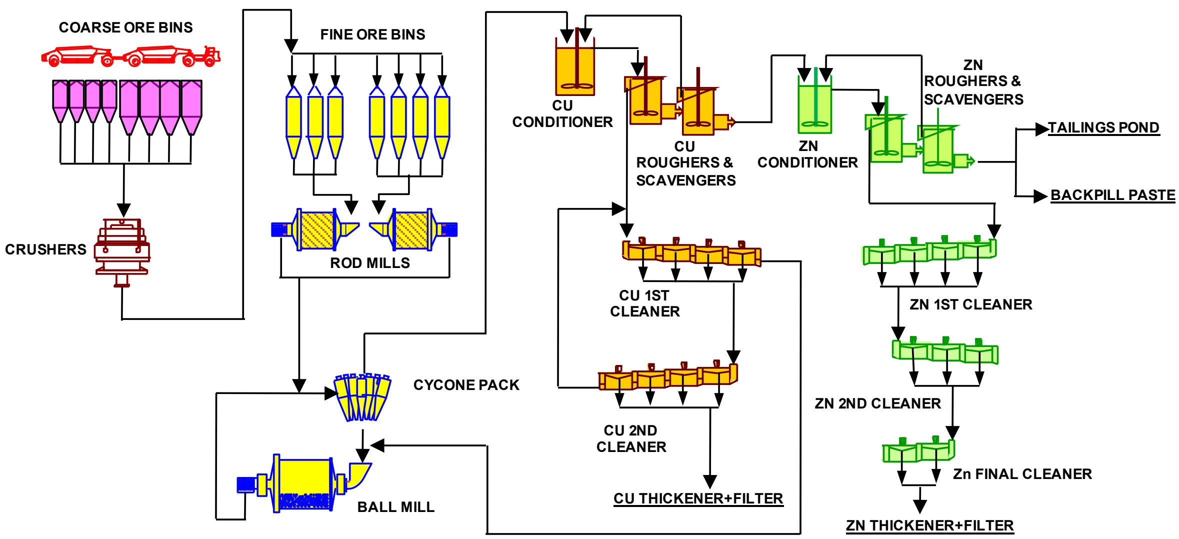

Figure 1 – Schematic flow diagram of Flin Flon concentrator

Copper rougher flotation concentrate is cleaned in two stages of counter current cleaners to produce a final copper concentrate which goes to the copper thickener and filter for dewatering. Copper rougher tailings are scavenged in 2 scavenger cells. The copper scavenger concentrate is returned to the front copper roughers. The copper scavenger tailings are directed to the zinc conditioning stage, in which zinc minerals are activated and conditioned with copper sulphate and lime slurry. The zinc flotation circuit is similar to the copper circuit but with three stages of cleaning. Final zinc scavenger tailings are split into two portions by a cyclone pack: the coarser tailings are used to prepare backfill paste. The fine portion is pumped to the tailings pond.

The three different ore sources from 777, Reed and Lalor Mines are of different mineralogy. The typical ore modal mineralogy is summarized in Table 1. 777 ore is high in Zn and low in Cu while Reed ore is high in Cu but low in Zn. The high percent of pyrrhotite in Reed ore makes Zn flotation difficult as pyrrhotite competes with sphalerite to react with copper sulphate. As a result, these two ores are usually processed in the commingling mode for moderate Cu: Zn ratio and Fe level.

Table 1 – Typical ore modal mineralogy

Ore Modal	777 (wt %)	Reed (wt %)	Lalor (wt %)
Chalcopyrite	3-7	4-8	0.4-3
Sphalerite	2-7	0.2-1	6-15
Pyrite	20-27	5-10	35-42
Pyrrhotite	3-7	60-75	5-9
Silica	35-55	4-10	3-10
Others	10-40	10-25	25-40

Fines Flotation

Since flotation was first introduced for sulphide mineral separation around a century ago there has been many technical developments, improvements and many millions of dollars spent on mineral flotation research. Much has changed but much has stayed the same. Alkyl xanthate, probably the most widely used flotation collector was patented by Cornelius Keller in 1925. Alternatively, flotation cell size has increased by orders of magnitude since flotation was developed, with 600 m^3 cells now employed.

Flotation recoveries have increased, operating costs have been reduced allowing lower grade ores to be treated economically but the problem remains, that the selective flotation of fine sulphide minerals – those less than 20 microns is still a major challenge. The reason for their poor selective recovery is well known; they have insufficient momentum to collide with a bubble (Dai, Fornasiero and Ralston, 1999; Duan, Fornasiero and Ralston, 2003). Increasing the fine particles momentum, either their mass or their velocity has been widely investigated and reported (Ahmed and Jameson, 1985: Ahmed and Jameson, 1989), but mostly focussed on fine particle velocity. These solutions have not necessarily been selective for the valuable sulphide (Ahmed and Jameson, 1989), or of practical use to increase the selective recovery of very fine particles. Selective sulphide mineral aggregation to increase the particle momentum by increasing its mass has had some success (Sivamohan, 1990; Holder 1994; Song *et al* 2000; Song *et al*, 2001; Song *et al*, 2001), but has suffered from the high cost to practically incorporate the methodology. A method that has been proven widely in process plants is the selective aggregation of fine sulphide minerals by utilising their paramagnetic properties. This methodology has been in use in plants for many years and some of the work has been published (Aslan, *et al*, 2010; Bott and Lumsden, 2009; Engelhardt, Ellis and Lumsden, 2005; Fleming, Wood and Lumsden, 2010; Holloway, Clarke and Lumsden, 2008; Rivett, Wood and Lumsden, 2007; Wilding and Lumsden, 2011; Zoetbrood, Vass and Lumsden, 2010).

Magnetic aggregation relies on the paramagnetism of commonly floated sulphide minerals like chalcopyrite, bornite, natural sphalerite, pentlandite and others. Even some minerals the literature claims to be diamagnetic, like galena, have been found in to be paramagnetic in some orebodies, probably due to iron in the galena crystal (Holloway, Clarke and Lumsden, 2008, Lacouture *et al* 2016).

Aggregating fine minerals is dependent on three physical characteristics; the mineral's size, the mineral's magnetic susceptibility and the strength of the magnetic field (Svoboda, 1987). It has been well documented that at the magnetic fields currently available with high gradient rare earth permanent magnets (>5000 gauss), with the magnetic susceptibility commonly found for sulphide minerals, that <10 micron sulphide minerals will aggregate. These aggregated mineral will have greater mass, so greater momentum and so will have a higher probability of colliding with a bubble. Increasing the collision efficiency will increase the flotation efficiency of the fine mineral (Duan, Fornasiero and Ralston, 2003).

Interestingly, and perhaps surprisingly, homogenous magnetic aggregation has been demonstrated at a number of sulphides processing plants (Aslan, *et al*, 2010; Wilding and Lumsden, 2011; Musuku, Muzinda and Lumsden, 2015; Lacouture *et al* 2016). Therefore, in the separation of two paramagnetic minerals there is not heterogeneous aggregation between the two different sulphides but homogenous aggregation of the same sulphides. That is, chalcopyrite aggregates with chalcopyrite, and sphalerite with sphalerite, not chalcopyrite with sphalerite. Moreover, it has been demonstrated that while both sulphides will aggregate homogenously, the selective flotation conditions employed ensure that only the mineral being actively collected increases in recovery. For instance, aggregated sphalerite's recovery will not increase in a copper circuit because the sphalerite has not been activated with copper sulphate. Just as importantly in this selective separation, the aggregated mineral that isn't being actively collected (sphalerite in a Cu circuit) recovers less; probably because larger aggregated minerals will entrain less in the froth.

FLIN FLON

The Flin Flon plant is a sequential Cu Zn float plant, recovering two concentrates. The chalcopyrite in the Cu concentrate and the sphalerite in the Zn concentrate were both measured and found to be paramagnetic. Their magnetic susceptibilities and the magnetic susceptibility of chalcopyrite and sphalerite reported in the literature are in Table 2. The magnetic susceptibility of the concentrates is comparable with the values reported in the literature.

Table 2 – Magnetic susceptibility of Flin Flon Cu and Zn concentrate

Mineral	Magnetic Susceptibility m^3kg^{-1}
Flin Flon Cu Concentrate	3.8×10^{-6}
Flin Flon Zn Concentrate	1.14×10^{-6}
Chalcopyrite (Svoboda, 1987)	1.6×10^{-6}
Sphalerite (Svoboda,1987)	$0.038\text{-}5.9 \times 10^{-6}$

The typical size distribution of final tails at Flin Flon Mill is plotted in Figure 2. Approximately 25% tails solid was less than 10 µm and 65% of tails solid was less than 45 µm. K80 of final tails is 68 µm. Based on the fraction assay of a few plant tails samples, the Cu lost to Cu scavenger tails is 75%-80% <45 µm and the Zn lost to final tail is 70%-75% <45 µm. This is the prime size for the magnetic system and shows that losses are predominantly in the fine fraction.

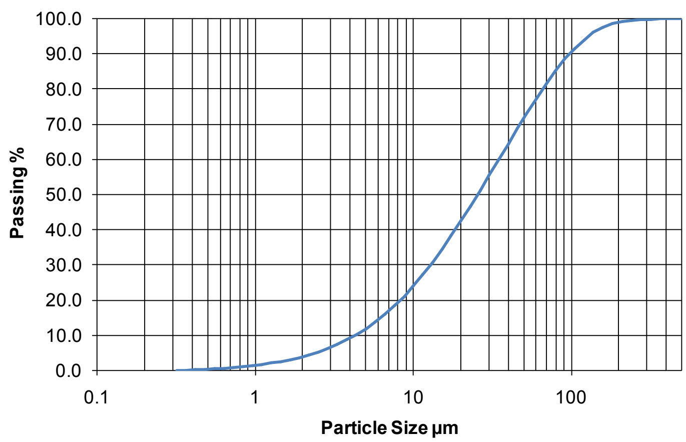

Figure 2 – Typical particle size distribution of final tails

Based on the testwork elsewhere (Aslan, *et al*, 2010; Wilding and Lumsden, 2011) it was expected that at Flin Flon the magnetic conditioning installed in the Cu circuit would both increase the Cu recovery to the Cu concentrate and reduce the recovery by entrainment of sphalerite in the Cu concentrate.

The Flin Flon ore has on average 1.5-2.5% Cu and 3-4.5% Zn. Current plant operation shows that the copper and zinc lost to either to payment (tails or non payable in concentrate) is in Table 3.

Table 3 – Copper and zinc losses at Flin Flon

Metal Stream	T/yr lost
Cu to Cu Scav Tails	3000
Zn to Cu Concentrate	5500
Zn to Final Tail	7000

At current metal prices, the losses are more valuable in the copper circuit than in the zinc circuit. Therefore, targeting the copper circuit is the optimum strategy because it is where most value is lost.

For this reason, and because impacting the copper circuit could have downstream impacts as it did at other sites meant the decision was made to test magnetic aggregation in the copper circuit.

EXPERIMENTAL

A plant trial for testing the magnetic system in Flin Flon Mill was carried out in 2017. A total of eight high strength high gradient rare earth magnets were installed in the Cu conditioning tank (photos are shown in Figure 3). Installation took about a day and a half. The statistical testing was initiated the following day. The experimental methodology was a paired t test, the most powerful statistical methodology for this type of evaluation (Napier Munn 2010). Two ON days were followed by 2 OFF days, and the test ran for about 4 months. Only the data obtained under normal operation conditions were used for the paired t test. They also took the normal process variation into account to compare the ON and OFF day performance.

Figure 3 – Magnetic tubes on top of the Cu conditioning tanks

Testwork at many other sites has shown that there is an equilibrium period required before the full impact of magnetic conditioning can be measured (Musuku, Muzinda and Lumsden, 2015; Lacouture *et al* 2016, Arnil, Zoetbrood, Gurieff and Lumsden 2018). This is not unexpected. Magnetic conditioning targets the fine mineral, but fine mineral is slow floating. It's the fine mineral that floats with low probability because of its poor collision with the bubble; therefore, most of the re-circulating load in the cleaner circuit is this slow floating fine mineral. Fine mineral that has floated to the rougher concentrate; reported to the cleaner, but then floats slowly in the cleaner and therefore, re-circulates back to the rougher feed via the cleaner tail. The re-circulating slow floating fine sulphide mineral in the cleaner may require multiple passes to report to concentrate. With three stages of cleaning this recirculation is amplified. Therefore, it is not surprising that any technology that targets fine mineral may well need an equilibrium period, to re-balance the re-circulating fines, before demonstrating the full effect in the plant.

Moreover, the test plan was to also evaluate the effect of magnetic conditioning on the subsequent zinc circuit; another reason why an equilibrium day is required to measure the full effect throughout the plant.

The necessity of the period of equilibration also occurred at Flin Flon. There was little difference between the first ON and the first OFF day, with these days not reaching equilibrium and being a blend of ON and OFF. However, there was a marked difference comparing the second ON and second OFF days. The results after an equilibrium day are the true difference.

RESULTS AND DISCUSSION

Copper Circuit Results

Analysing the plant data is relatively simple with the paired t test. The key results for the copper circuit are given in Table 4.

Table 4 – Magnetic Conditioning Results in Copper Circuit

	%Cu Rec.	% Cu in Conc.	%Zn in Cu Conc.	%Zn Rec.
Magnetic Conditioning ON	93.6	24.5	3.1	6.9
Magnetic Conditioning OFF	92.8	24.2	3.3	7.0
Difference	0.8	0.3	0.2	0.1
Level of Confidence	99%	81%	94%	low

The results show an increase in copper recovery of 0.8% to a very high 99% level of confidence. This is a selective increase in copper recovery with no loss in copper concentrate grade. As the head grade is a key fact to determine metal recoveries in Flin Flon Mill's Cu and Zn circuits. The head grades of magnetic ON and OFF periods were also t test paired and recognized as no difference to high confidence. Possibly, if the test and continued and more data pairs were collected the increase in the certainty of the copper concentrate grade increase with magnetic conditioning may have occurred. However, with the increase in copper recovery to such high confidence and the financial benefits of this increase so substantial, there was no incentive, other than scientific, to continue the test to increase the certainty of the copper concentrate grade increase. Certainly, the magnetic conditioning produces an improved copper grade – recovery curve.

The sphalerite flotation in the copper circuit is interesting. At other similar sites a reduction in zinc grade in copper concentrate has been measured (Aslan, *et al*, 2010; Wilding and Lumsden, 2011). The decrease in zinc recovery to copper concentrate with magnetic conditioning at Flin Flon was very minor and at low confidence, but the reduction in zinc grade in the copper concentrate was to high confidence and about 8% relative. This does suggest better copper- zinc selectivity – increased copper recovery at the same zinc recovery and a reduction in entrainment of zinc in copper concentrate.

The reason why there was a reduction in zinc grade in copper concentrate to high confidence, but not in zinc recovery to copper concentrate to high confidence is due partly to the variability. The standard deviation of the paired difference in zinc grade in copper concentrate was quite low at about 3 times the mean difference. But for zinc recovery to copper concentrate, the standard deviation of the paired difference in zinc recovery to copper concentrate was very high at about 27 times the mean difference. This high variability in the zinc recovery to copper concentrate means that measuring a reduction in zinc recovery to copper concentrate is extremely difficult.

Why is the zinc recovery to copper concentrate so variable, whereas the zinc grade in zinc concentrate is not at Flin Flon? Part of the reason is mathematical. The circuit is operated to a copper concentrate grade, so necessarily there is a limited range for the zinc concentrate grade in copper concentrate. If a 25% copper concentrate grade is targeted, then it is impossible for the zinc in copper concentrate to be higher than about 15% if sphalerite is the only diluents. At Flin Flon pyrite is the primary diluent in the copper concentrate, so the maximum zinc in copper concentrate will be much less than 15%. The actual maximum zinc in copper concentrate recorded during the test was 5.5%Zn. whereas, of course zinc recovery to copper concentrate can theoretically be 100%, so the range in values for the zinc recovery is much higher than for zinc grade.

However, one of the main reasons for the high variability in the zinc recovery to copper concentrate is the variability in the ore feed. Flin Flon treats ore from three sources, 777, Lalor and Reed. Each of these ores is quite different. 777 and Reed are blended but Lalor is treated as a campaign. Of importance in discussing the zinc recovery to copper concentrate variability and the difficulty in balancing optimising copper recovery to copper concentrate and minimising zinc recovery to copper concentrate is the feed grades of the three ores. Even slightly changing blends of these ores can alter the circuit varying the zinc recovery to copper concentrate. Average grades and the Cu: Zn ratio in the feed is given in Table 5.

Table 5 – Flin Flon Ore Copper and Zinc Ratio

Ore	% Cu	%Zn	Cu:Zn ratio
Reed	3.5	0.5	7:1
777	1.5	5.5	0.27:1
Lalor	0.7	6.5	0.11:1

The large difference in metal feed content of these two blended ores, Reed and 777 ores does present challenges when trying to optimise the plant operation and balance maximising copper recovery and selectively against zinc in copper concentrate.

Finally, the 777/Reed ore blend has a similar copper and zinc grade, therefore, operating the plant to optimise copper recovery and copper-zinc selectivity means that the balance can easily slip to an incremental increase in copper recovery but a large increase in extra zinc recovery to copper concentrate. For the same copper recovery and copper and zinc in concentrate, halving the Cu: Zn ratio in the feed halves the zinc recovery to copper concentrate. Therefore, the lower the Cu: Zn ratio in feed reduces both the variability and the percentage of zinc recovered to copper concentrate. For other mines where the Cu: Zn ration in feed is much lower, losing the recovery balance in the copper circuit does not have such large consequences for the zinc circuit. When Lalor ore is campaigned the zinc recovery to copper concentrate is on average about half that of the 777/Reed blend, and the standard deviation of the paired difference is about 3.5 times the mean difference or around 10% of the relative standard deviation for the 777/Reed paired results.

At some sites, where the silver and gold mineralogy is either paramagnetic or the precious metals are closely associated with the paramagnetic minerals, magnetic aggregation has increased their recovery (Engelhardt, Ellis and Lumsden, 2005; Fleming, Wood and Lumsden, 2010; Holloway, Clarke and Lumsden, 2008; Rivett, Wood and Lumsden, 2007). Daily gold and silver recovery calculations at Flin Flon are of low reliability because the plant feed sample is a coarse sample taken from the rod mill discharge. Nugget effect of the sample assay makes the Au and Ag recovery calculation very variable. The testwork found no difference in gold or silver recovery to the copper concentrate to high confidence.

<u>Zinc Circuit Results</u>

The increase in zinc recovery to zinc concentrate with magnetic conditioning is not to high confidence. This is despite the magnitude of the increase being 20% greater than the increase in copper recovery to copper concentrate. It is the greater variability in the zinc recovery to zinc concentrate results that mean a larger difference is not to high confidence. And this variability is due to the variable recovery of zinc to copper concentrate. The lower zinc in final tail is approaching a high level of statistical confidence, and given that the feed grade for both conditions was very similar (4.45%Zn ON and 4.52%Zn OFF) this lower tail grade at relatively high confidence is indicative of an increase in Zn recovery. The results for the zinc circuit of the ON OFF test in the copper circuit are given in the table below.

Table 6 – Magnetic Conditioning Results in Copper Circuit

	%Zn Rec.	%Zn in Conc.	%Zn in Tails
Magnetic Conditioning ON	85.4	52.0	0.38
Magnetic Conditioning OFF	84.4	51.7	0.44
Difference	1.0	0.3	0.06
Level of Confidence	low	low	86%

It was not considered economically advantageous to continue the testwork to determine whether more data would have given higher confidence for any of the zinc circuit results. The copper recovery was to high certainty and that justified the introduction of magnetic conditioning independent of the zinc results, which certainly weren't worse with magnetic conditioning.

CONCLUSION

Magnetic conditioning testwork in the copper circuit at Flin Flon has shown that the paramagnetic chalcopyrite recovery can be increased with no increase in the paramagnetic sphalerite recovery to copper concentrate; despite both minerals being paramagnetic. This is in effect an increase in chalcopyrite-sphalerite selectivity, and supports the hypothesis that magnetic aggregation is homogeneous.

At Flin Flon copper recovery to copper concentrate increased by 0.8% to very high confidence. However, despite a larger increase in zinc recovery to zinc concentrate, this increase in zinc recovery was not to high confidence because of the higher variability in zinc recovery. The increased variability in zinc recovery to zinc concentrate is because there is substantial variability in the zinc recovery to copper concentrate due to the relative similarity in the Cu and Zn content in the feed and the selectivity problems this presents to the copper flotation.

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