Cleaner Flotation Circuit Optimization at Oyu Tolgoi - A Plant Trial of Magnetic Conditioning.

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Abstract

The Oyu Tolgoi concentrator processes 120,000 t/day of ore in a conventional flotation plant consisting of rougher and cleaner-scavenger tank cells, with column cells as the secondary cleaner stage. The operation is transitioning from open-pit chalcopyrite ore to a higher-grade underground ore with a high bornite content. The changing ore mineralogy and higher grade have necessitated modifications to the flotation circuit. Notably, additional flotation capacity has been installed, despite no change to the overall planned throughput.

Consistent with Oyu Tolgoi's metallurgical strategy to implement best practices in flotation; magnetic conditioning was trialled in the cleaner flotation circuit to improve fine copper flotation recovery. A paired t-test was conducted to statistically evaluate the impact of magnetic conditioning on Cu flotation recovery and concentrate grade. The results are presented in this study.

Automatic plant samples were split into routine composite plant samples and specialized project samples. The project samples were sized at 25µm before assay and both the composite and project samples were utilised in the evaluation. However, the magnitude of the measured copper recovery improvement was different, depending on which samples were used in the evaluation. The confidence levels of the measured difference were also different. This discrepancy raised a critical question: 'Are routine composite samples, commonly used for plant monitoring, more reliable than specially collected and sized samples for project-specific testwork?' This paper examines the differences between routine and project samples, compares outcomes, and explores the possible reason for the difference and the implications for future metallurgical plant test evaluations.

An additional observation from the trial was that the circuit change took a shift to accurately measure the change in the cleaner circuit performance, consistent with prior testwork, that suggested a delay of up to three shifts on a 4 shift ON 4 shift OFF test schedule. These findings contribute valuable insights into the dynamics of operational changes in large-scale flotation circuits. It under-scores the importance of both sampling strategy and data timing in plant-scale evaluations.

Key Words: Oyu Tolgoi, copper flotation, fine particles, magnetic conditioning

Introduction

OT History

The Oyu Tolgoi mine is located in the South Gobi desert an arid region about 550km south of the Mongolian capital of Ulan Bataar. Copper has been mined and recovered from this area since the bronze age, around 3000 years ago, with many small scale workings discovered (Porter, 2016). Modern exploration of the area in the early 2000's discovered a large copper, gold and molybdenum deposit and mining operations began in 2011, with first concentrate trucked in 2013.

The mine is a joint venture between Rio Tinto and the Mongolian government and was initially an open pit mine, but now also operates an underground block cave mine. Oyu Tolgoi is one of the world's largest new copper-gold mines, and projected to become one of the largest copper concentrate producers during its peak production years.

OT Mineralogy

The deposit consists of 7 separate porphyry clusters in the deposit and they are some of the world's largest high grade porphyries (Porter, 2016).

The open pit ore is primarily a chalcopyrite ore and with minor gold content. However, the underground ore is higher grade with more bornite content. Both ores have minor covellite and chalcocite. The underground ore also contains gold. The magnetic property's of the Cu sulphide minerals, from the two ore types was investigated from the recovered concentrate. An AGICO MFK1-A kappabridge magnetometer was used, to measure the magnetic susceptibility of the total concentrate sample. A Franz isodynamic separator was used to separate the concentrates from the two ores into a strongly paramagnetic fraction and a weakly paramagnetic fraction. Optical microscopy of the two fractions was undertaken to identify the Cu sulphide minerals present in the fractions and estimate their concentration. The results are summarised in Table 1.

Table 1: Magnetic separation and magnetic susceptibility results for bornite and chalcopyrite ore.

Ore type	Cp:Bn ratio	Magnetic susceptibility total sample x 10^{-9} m^3kg	%Strongly paramagnetic	% Weakly paramagnetic
Underground	39:50	433	66	33
Open Pit	85:6	483	40	59

The bornite concentrate has a higher content of the strongly paramagnetic fraction compared to the chalcopyrite fraction, despite the total sample having a slightly lower magnetic susceptibility.

The Cu mineral distribution in the two paramagnetic fractions is given in Table 2.

Table 2: Cu mineral distributions by fraction

Ore Type	Weakly paramagnetic fraction		Strongly paramagnetic fraction	
	Chalcopyrite	Bornite	Chalcopyrite	Bornite
Underground	40.5	57.2	44.6	54.7
Open Pit	83.5	5.6	86.8	6.5

For both ores the bornite : chalcopyrite ratio is similar for the two paramagnetic fractions.

The difference in magnetic susceptibility between chalcopyrite and bornite is reported as being orebody dependent (Gaudin et al, 1943). Gaudin et al (1943) separated the copper minerals for copper concentrates from 4; Cotapaxi, New Coralina, Arthur and Anaconda. For each the bornite was more strongly paramagnetic than the chalcopyrite. The separation of the Cu minerals into the different magnetic fractions also showed that the magnetic susceptibility of the bornite was not identical across the ores, but varied. Chalcopyrite magnetic susceptibility also varied across the concentrates. Therefore, the magnetic susceptibility of the Cu minerals was orebody dependent. Contrary to Gaudin, Svoboda (1987) reports chalcopyrite as being more strongly paramagnetic than bornite.

<u>OT Flowsheet</u>

The OT flotation flowsheet is in Figure 1.

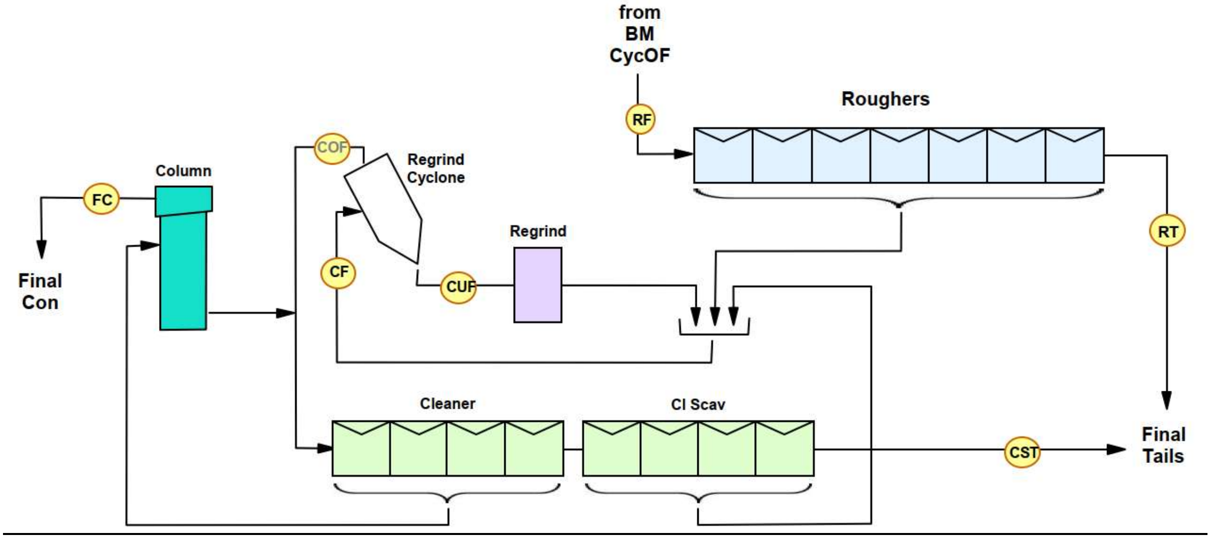

Figure 1: OT Concentrator Flotation Flow Sheet

<u>Magnetic Aggregation</u>

Gaudin et al (1931) was the first to report the effect of particles size on flotation recovery and the poor flotation of fine minerals. Over the past decades this phenomenon has been extensively investigated. Duan et al (2003) modelled fine mineral flotation and showed that the poor recovery of fine mineral was due to poor bubble-particle collision because of the low momentum (mass) of the fine particles. Only increasing mass or velocity will increase fine particle momentum and Duan et al (2003) showed that increased velocity was detrimental to coarse particle flotation due to coarse particle detachment from the bubble.

Aggregation of fine particles increases their mass and momentum but the aggregation of the fine particles must be selective, otherwise the purpose of flotation – selective separation is lost. The known magnetic susceptibility of the common Cu sulphides, chalcopyrite, bornite and natural chalcocite, as well as some other sulphides is widely reported (Svoboda, 1987). Just as importantly, the low to negligible magnetic susceptibility of gangue and pyrite ensures the selectivity of magnetic aggregation and improves flotation selectivity.

Magnetic aggregation is achieved by magnetising the slurry in a magnetic conditioning stage prior to or during at the initial stage of flotation. Many papers have been published reporting plant test results with magnetic conditioning, reporting selective increases in sulphide mineral recovery: copper sulphides (Rivett et al, 2007), sphalerite (Lacouture et al, 2016), galena (Holloway et al, 2008) , pentlandite (Musuku et al, 2015), PGM's (Khumalo et al, 2022) and precious metals (Rivett et al, 2007; Holloway et al, 2008).

Plant Testing

Statistical plant testing to determine whether changes in operating parameters are beneficial has been an area of development over the last 50 years. Measuring a small but very valuable difference to a high statistical certainty, in a variable mineral separation plant is an experiment that needs careful planning. To provide confidence to management that the difference is due to the parameter change, rather than random plant variation, requires experimental rigour. Much of this method development has been undertaken by Napier-Munn (2010) who has published widely.

Process plants are notoriously variable. The variability stems from the ore, the operators, and all the other variables present in a plant. Generally, in large operations, the ore variability isn't by the hour or minute, but over a longer time frame. The head grade or mineralogy may change over a longer time frame. Other variability can be on a longer or shorter time frame. Operations try to keep ore changes to a minimum by blending to ease the operational changes and reduce spikes and dips in operation.

Generally, where the two conditions can be operated alternately, a paired 't' test is the most powerful method (Napier-Munn, 2010). Its power is derived from minimising the plant variability by alternating the two conditions continuously over a short time frame, multiple times.

Another plant development that has assisted in the development of plant statistical testing has been good automatic plant sampling.

Plants automatically collect regular (shift) samples, prepare and assay these samples to monitor performance and for metallurgical accounting. This is a 24/7 operation using routine standard methods of sample preparation and analysis. Plant laboratories generally have a series of standards so that the chemical analysis is checked, but generally, there is no routine QC of sample collection and sample preparation, rather these are standardised to limit sources of error.

Most plants undertake plant projects. Projects are by their nature non-routine. They are generally a unique, specialised operation using new methods or normal methods in a new way. Often those involved in projects are more specialised and skilled than those doing routine work because in projects, observation is important and modification is often necessary.

Experimentation

Plant Testing at Oyu Tolgoi

For the magnetic aggregation plant testwork at Oyu Tolgoi the routine automatic plant samples were used to measure plant performance. But to add rigour to the test and to see the affect of magnetic conditioning on the targeted fine Cu minerals the automatic samples collected, were dried and then split into two samples and processed in two different ways. One sample became the routine shift sample and was processed – prepared and assayed as the routine shift sample. The other sample was treated as a project sample. This sample was sized at 25 µm, and both fractions dried, prepared and assayed.

Generally, the plant engineer has more confidence in the routine sample because the operator who prepares and assays the sample is experienced. Also, there are less steps taken with the routine sample, compared to the special project sample that is sized, so less opportunity for errors to occur. But, generally the operator who prepares and assays the routine samples is less skilled than the project operator and it is possible that the routine operator is under time pressure and may takes short cuts, or because the task is routine becomes complacent or distracted. However, the project operator tends to be more skilled, more involved in the project, more focussed on the outcomes, has more time and has more 'buy in'. It is true there are more steps for the project sample, more opportunity for error, but there are ways of overcoming errors in this extra step (sizing). Cross contamination can be negated by careful cleaning of sieves, having one sieve and work station for tails, a separate sieve and work station for feed and a separate sieve and work station for concentrate. This helps to reduce the possibility of contamination.

The plant test was started at the completion of the installation of the magnetic conditioning equipment in the first two cells of each of the three cleaner rows.

In a cleaner circuit where there are re-circulating streams a change in condition will usually take a period of time to permeate the whole cleaner circuit. The time period will vary from operation to operation. But in the case of magnetic conditioning that targets fine flotation – the slowest floating minerals in a cleaner circuit, the time period for full permeation of the circuit may be lengthy. Others (Medina et al, 2022) have shown that it can take as long as 3 shifts for the change to be fully measured in the circuit. It can be seen from the Oyu Tolgoi flowsheet that there are a number of re-circulating streams in the cleaner circuit. The cleaner scavenger concentrate re-circulates back to the head of the cleaner and the column tail re-circulates back to the cleaner. Because of this recirculation – some mineral may re-circulate a number of times, therefore, a 4 shift ON OFF test was employed (2 days ON OFF).

Cleaner circuit automatic samples; cleaner feed, cleaner scavenger tails and final concentrate were used to measure cleaner operation. Shift (12 hour) samples were collected and split with one fraction being sent for special project sizing and analysis at 25 µm and the other fraction being analysed as the routine plant sample for that shift. The sizing is a method initially developed at Northparkes (Rivett et al, 2007) for testing magnetic conditioning. Because the magnetic conditioning targets fine minerals looking at the metallurgical performance in the fine fraction removes the noise generated by the coarser fraction.

The Oyu Tolgoi operation is very steady and all data was used, except about 10% of the shifts where tonnage was low, with plant feed of 50,000t/shift being the cut point. The data was screened for outliers as recommended (Napier Munn 2010) but no outliers were detected.

Results and Discussion

Time Delay for the Change to Permeate the Cleaner Circuit

The 2 day ON OFF test operated for 4 months. Comparing the difference in Cu cleaner recovery and assay with time from the change showed that the Cu recovery difference between ON and OFF for the first shift was completely different to the Cu recovery difference between ON and OFF for the 2nd – 4th shift. Figure 2 clearly shows that the Cu recovery for the first shift after the change, ON or OFF, was a mix of ON and OFF conditions and was not a representative measure of the true ON or OFF performance. The difference in Cu recovery between ON and OFF for shifts 2-4 were similar.

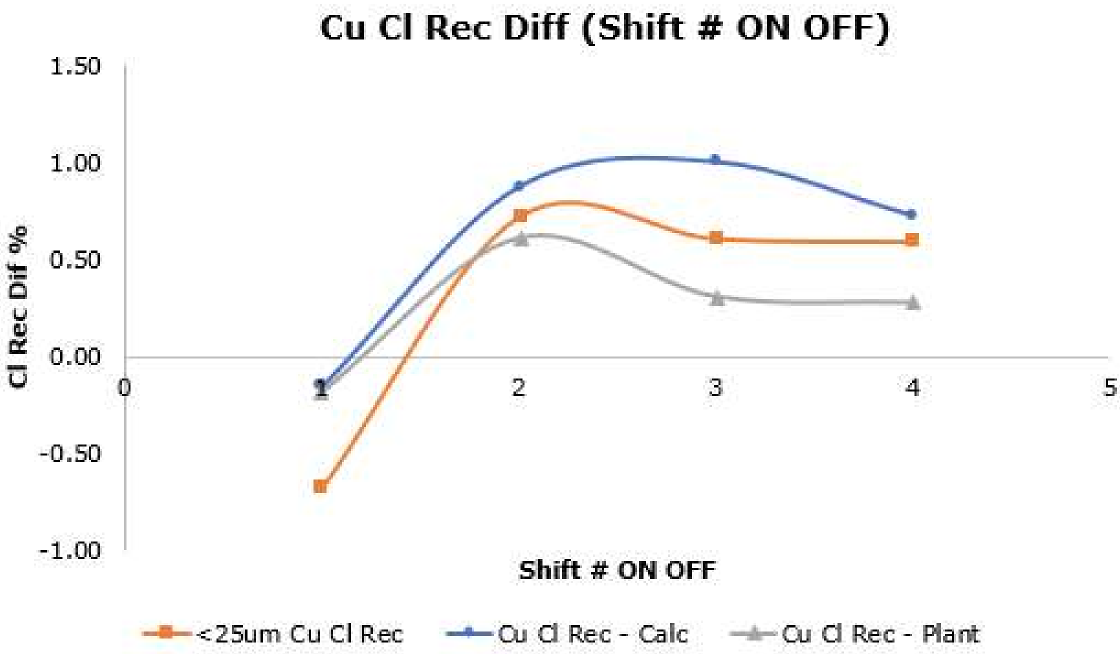

Figure 2: Difference in Cu recovery between ON and OFF by shift number from change.

There were 112 shifts (56 pairs) of 2nd - 4th shifts of plant data. There were 53 pairs of 2nd - 4th shifts of special project samples sized (some missing assays reduced the number). The analysis presented here compares the 106 shifts where there was both sizing and plant data.

<25 micron Cleaner Results

The special project samples that were sized show a clear improvement in the <25 µm flotation performance with magnetic conditioning. There is a lower average % Cu in tail, a higher average Cu recovery and an increase in average final Cu concentrate grade for this fraction, feed grades were the same. The results are summarised in Table 3.

Table 3: <25 µm average results for magnetic conditioning

	<25 µm %Cu Cl Sc Tl	<25 µm %Cu Cl Rec	<25 µm %Cu Cl Conc	<25 µm %Cu Cl Fd
Magnetic conditioning ON	0.298	94.95	24.93	4.90
Magnetic conditioning OFF	0.342	94.30	24.33	4.92
Difference	-0.044	0.65	0.59	0.02
Lvl of confidence	99%	98%	96%	Low

It is interesting to see the very high levels of confidence attesting to the steady operation of the plant/ore and the quality of the sampling and assaying, as well as the magnitude of the difference between the conditions in the <25µm fraction.

<u>Comparison of Routine and Project Results</u>

Having established a change in the fine Cu flotation in the cleaner it is interesting to look at the two methods of measuring circuit performance, project samples and routine samples, to see whether they correlate. The calculated head from the two size fractions of the project samples was compared with the measured result from the routine sample. These results are in Table 4.

Table 4: Project and routine average results compared

	%Cu Cl Tl		%Cu Conc		%Cu Cl Rec	
	Project samples	Routine	Project samples	Routine	Project samples	Routine
Magnetic conditioning ON	0.309	0.282	21.57	21.64	94.96	95.23
Magnetic conditioning OFF	0.360	0.319	21.15	21.40	94.02	94.77
Difference	0.051	0.037	0.41	0.24	0.93	0.45
Level of confidence	99%	99%	92%	91%	99%	97%

The results from analysing the plant by the two methods – routine samples and special project samples are similar in confidence, vary slightly in magnitude, but are in the same direction and so the same conclusion can be made – magnetic conditioning is selectively increasing cleaner circuit flotation performance to high confidence.

However, the project samples are measuring about a 10% higher average %Cu in cleaner tail, for both ON and OFF samples and a larger reduction in Cu in tail with magnetic conditioning. This measures about double the average increase in Cu recovery with magnetic conditioning. While this wasn’t critical in this test because of the large benefit and high confidence, this could be important if the economic benefit was marginal, or if the level of confidence was closer to the mine determined threshold.

Comparison of Routine and Project Assays

The reason for the difference in cleaner tail between the two methods is important to investigate, particularly for future testwork. The routine samples are measuring on average 0.300%Cu in cleaner tail, while the project samples are measuring on average 0.335%Cu in cleaner tail – around a 10% difference. However, the cleaner feed and cleaner concentrate are measuring negligible average difference between the two samples. The average results are summarised in Table 5.

Table 5: Comparison of average assays for the two sets of cleaner samples

	%Cu Cl Feed	%Cu Final Conc	%Cu Cl Tail
Average Routine Assay	4.80	21.52	0.301
Average Project Assay	4.86	21.36	0.335
Difference	0.06	0.16	0.034
Lvl of Confidence	low	low	>99%

The average feed and concentrate assays correlate, and there is no statistical difference in their assays. But for the cleaner tail the significant difference needs to be investigated.

The usual, most common or obvious reason for the cleaner tail difference is that in the extra steps of the project sample analysis (sizing and filtering) results in contamination of the cleaner tail. But is this superficial explanation valid? Especially for a 10% different outcome between methods, if separate sieves and work stations are employed for the cleaner tail sample sizing.

Comparison of Routine and Project Cleaner Tail Assays

Investigating the difference in the cleaner tail assays between the routine and project assays it is useful to look at other cleanertail assays, Au and Fe. These results are in Table 6.

Table 6: Cleaner tail assay comparison Cu, Au and Fe

	%Cu Cl Tail	g/t Au Cl Tail	%Fe Cl Tail
Average Routine Cleaner Tail Assay	0.301	0.35	11.05
Average Project Cleaner Tail Assay	0.335	0.38	11.24
Difference	0.034	0.03	0.19
Lvl of Confidence	>99%	>99%	87%

Gold is probably not a good element to assist with the investigation of the difference in methods due to its 'nugget' effect and lower assay accuracy at low concentrations. But Fe assays are reasonable to use even though the level of confidence between the two methods is not above 90%. The lower confidence level for the Fe difference is due to their higher variance compared to Cu.

The sample mass used in the project samples was about 200g. We can calculate the average amount of 'contamination' and then model the average weight and assay of the 'contaminant' that is required to change the average tail assay. For a contamination of mass of 0.25%, 0.5%, 1% and 2.5% the assays can be calculated. This modelling is in Table 7.

Table 7: Modelled contamination for cleaner tail

200g Project Sample	0.5g(0.25%	1.0g(0.5%)	2.0g(1.0%)	5.0g(2.5%)
% Cu assay of contaminant	14.5	7.4	3.8	1.7
% Fe assay of contaminant	88	50	31	19

Contamination of a sample would be expected to be low in weight. A high weight of contaminant is not contamination but mixing of samples. Using the contamination weights above, the contamination must be > 1g (0.5%), (88% Fe + 14.5% Cu is not possible). But there are no samples on site with the Cu and Fe assays that match the Fe and Cu assay of the potential contaminant of 0.5% to 2.5%. The cleaner feed has an assay of around 3.8% Cu, but the Fe is around 15% Fe, not 31% and there are no samples with low Cu high Fe. Therefore, it is difficult to see how on average the cleaner tail project samples could have been contaminated in the extra steps of processing.

Careful investigation appears to show that contamination of the project samples with the extra steps is unlikely to be reason for the higher tail assay for the project samples because small contamination cannot account for the difference between project assays and routine assays.

Is it possible that the routine sample preparation and assaying under-assays the Cu and Fe in cleaner tail? Is the time pressure to produce results, or complacency the cause of the lower routine assay results? Incomplete digestion? But the feed and concentrate methods have excellent correlation. Or is there some other factor that under reports the metal content in the routine cleaner tail assay? This should be investigated more thoroughly.

The authors have unpublished data from another minesite that shows a similar result – better results with project sample compared to routine samples. So perhaps this difference is more prevalent than expected.

Conclusions

Oyu Tolgoi has undertaken detailed experimental testwork to improve their cleaner circuit performance and incorporate best practise. The statistical paired t test of the magnetic conditioning technology has significantly improved the selective Cu recovery and the final Cu concentrate grade to high confidence. This has been due to a strong increase in the <25 micron metallurgical result – recovery and concentrate grade. The result is financially beneficial to the operation, with a short financial payback.

Two methods were used to measure the change in cleaner circuit performance with magnetic conditioning. The automatic plant samples were split in two and one split assayed as routine plant samples and one split sized and assayed as special project samples. For the feed and concentrate samples the correlation between the two methods over 4 months is excellent - there is no difference in the measuring methods. But for the cleaner tail sample, that is central to recovery calculations, the two methods both showed a reduction in average tail grade with magnetic conditioning to high confidence, but with a 10% difference in average cleaner tail assay between the two methods. Contamination might have been expected to be the reason for the higher cleaner tails assay with the project samples, due to the more steps in their preparation, but a more careful investigation does not support this explanation. There are some other possible reasons but without further investigation it is not possible to be conclusive as to why the project samples gave a higher assay. More work needs to be undertaken to identify the explanation for this result difference.

Finally, the testwork showed that one shift equilibrium was required to see the true difference between magnetic conditioning ON and OFF.

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