PLANT TESTING MAGNETIC CONDITIONING ON KENNECOTT'S Cu-Mo PORPHYRY ORE

Fred Rudloff, Rio Tinto Kennecott, Salt Lake City, UT
John Moyo, Rio Tinto Kennecott, Salt Lake City, UT
Isaac Boadi, Rio Tinto Kennecott, Salt Lake City, UT
Mitchell Struble, Rio Tinto Kennecott, Salt Lake City, UT
Christos Karageorgos, Ausmetec Pty Ltd, Sydney, Australia
Barry Lumsden, Ausmetec Pty Ltd, Sydney, Australia

Abstract

Over it's more than 100-year history, the Kennecott operation has often been at the forefront of innovation; driven by the demands of the lower grade ore-body and the higher costs of operating in the US where wages are generally higher and regulation more restrictive. One way of reducing operating costs in c/lb is to increase the lbs produced at minimal cost.

Despite the relatively coarse grind at Kennecott - about 30% >150µm, approximately 20% of the Cu lost to tail is liberated chalcopyrite in the <20µm fraction, and about 30%-40% in the <37µm fraction. In 2020 Kennecott undertook a detailed plant scale test of the magnetic aggregation technology to increase copper recovery by reducing fine copper losses.

A paired statistical plant test of magnetic conditioning on one rougher line showed a 1.12% increase in Cu recovery to 97% statistical confidence.

The next challenge, unforeseen at the start of the project, was the fabrication and transportation to site of the equipment for the three remaining rougher rows, during the severe supply-chain constraints of the Covid pandemic in 2021. This resulted in delays and unforeseen costs as world-wide transportation became chaotic, particularly transportation via west coast USA. Nevertheless, the project was completed and commissioned, with only minor delays and cost increases, due to a flexible approach to overcoming the hurdles encountered.

Introduction

The Kennecott Utah Copper Mine is located within commuting distance, south-west of Salt Lake City, Utah. Open pit mining began on the relatively low-grade ore in 1903. Because of the lower grade ore at Kennecott, innovation was necessary to maintain profitability. Kennecott was the first open pit porphyry copper mine and was either an early adapter or initiator of many of the innovations in mining and sulphide mineral processing, including; flotation, SAG milling and Cu-Mo flotation separation (1). The world's first flotation separation of Mo from Cu concentrate was carried out at Kennecott in 1936 (1). In 1998, Kennecott had produced 17million tonnes of Cu, more Cu than any other single mine in the world (2).

Kennecott Mineralogy

The Bingham Canyon ore is a Cu-Au-Mo porphyry ore in multiple host rock types, from igneous to metamorphic. The copper minerals are primarily chalcopyrite with some bornite. There are minor secondary copper minerals, chalcocite and covellite. The chalcopyrite is mostly associated with quartz and feldspars.

The magnetic susceptibility of the copper concentrate produced from the mine is 1570 x 10^{-9} m^3kg^{-1} consistent with the magnetic susceptibility of chalcopyrite reported in literature as 1596 x 10^{-9} m^3kg^{-1} (7).

The chalcopyrite losses are primarily in the +150 micron and -20 micron fractions.

Kennecott Flowsheet

The Kennecott flowsheet is crushing followed by a SAG and ball mill grinding. Ball mill cyclone overflow reports to 4 parallel rougher flotation lines. The rougher and scavenger concentrates are reground before reporting to the cleaning circuit, where the cleaner concentrate reports to the Cu-Mo circuit and the cleaner tails to final tails. Figure 1 details the current Kennecott flotation flowsheet.

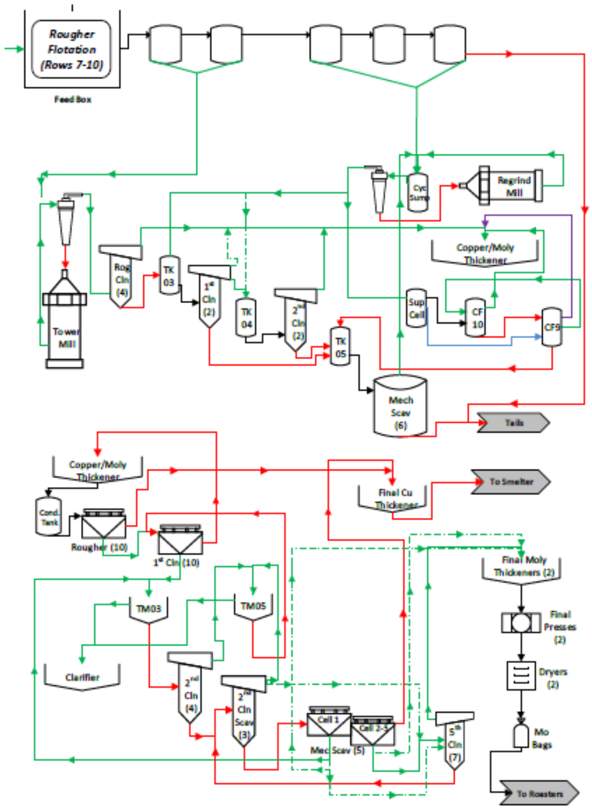

Figure 1. Kennecott flotation flowsheet

Fine Sulphide Mineral Flotation

The flotation recovery of fine sulphide minerals <20 µm in size, is an ongoing and increasing challenge in mineral processing. Finer grinding is becoming more common as grinding technology improves and ores become more complex. High recovery of sulphide minerals in the 20 µm - 75 µm is well known, while the poorer >75 µm recovery is generally a liberation problem, or due to detachment of the coarser particles from the bubble. The poor recovery of the <20 µm sulphide mineral has been shown to be due to the poor collision efficiency of the mineral with the bubble, because of the mineral's low particle momentum (3). Increasing the particle momentum is one solution, but increased mineral velocity is detrimental to the coarse recovery because the increased velocity increases turbulence that increases coarse particle-bubble detachment (4); reducing coarse mineral recovery. Moreover, increasing velocity is non-selective because the recovery of gangue and pyrite also increases (4). Increasing <20 mineral momentum by increasing particle mass, at the same velocity, is not detrimental to coarse recovery. Increasing fine mineral mass by selective aggregation of the valuable sulphide mineral has been investigated by a number of researchers using a number of difference methods, including high intensity conditioning (5) and floc-flotation (6).

However, high intensity conditioning and floc-flotation are expensive in power consumption, reagent usage or require long agitation times. Mines in the age of zero carbon emission's promises are under pressure to reduce power consumption, and anyway power is becoming a more expensive commodity as decarbonising becomes more widespread. Some mineral processing plants power costs can be up to 30-40% of processing costs. The reagents used are also derived from the oil or gas industry, another industry threatened by the zero carbon emission goals.

Magnetic aggregation, a technology focussed on the paramagnetic characteristic of some sulphide minerals offers a selective, low cost, low carbon emission solution to increasing fines recovery. The method has negligible energy consumption and a negligible operating cost.

Magnetic Conditioning

All minerals are either, ferromagnetic, paramagnetic or diamagnetic. In sulphide flotation, the valueless gangue and pyrite is generally diamagnetic (quartz) or has a minor magnetic susceptibility (pyrite) (7). However, some valuable sulphides can be paramagnetic; even strongly paramagnetic. Chalcopyrite, bornite, natural chalcocite and sphalerite are valuable sulphide minerals that are paramagnetic and recovered by flotation (8).

Magnetic aggregation is selective because the non-sulphide minerals are diamagnetic or not strongly paramagnetic, so unaffected by magnetic fields. Furthermore, plant testwork has shown that even when two strongly paramagnetic sulphide minerals are present the aggregation is homogeneous, rather than heterogeneous. So, in a sequential chalcopyrite-sphalerite separation, the chalcopyrite recovery increases in the copper concentrate and the sphalerite recovery increases is the zinc concentrate. It has also been shown that the sphalerite recovery is reduced in the copper concentrate because the aggregated fine sphalerite is entrained at lower rates in the copper concentrate (9).

Magnetic aggregation is therefore, selective, low cost with a negligible carbon footprint, satisfying the requirements of modern flotation.

High strength, high gradient rare earth permanent magnets containing neodymium were developed by General Motors and Sumitomo, independently in 1984. They are the most widely used rare earth magnets and because of their higher strength to weight ratio are increasingly replacing ferrite magnets. They are central for much of modern technology. It is estimated that each windmill contains about 2000kg of rare earth magnets.

Magnetic aggregation of the sulphide minerals in a slurry is achieved by inserting high strength high gradient permanent rare earth magnets in the flotation slurry, either in the flotation cell or in the flotation conditioner. One complication that arises with permanent magnets is that any ferromagnetic material in the slurry, such as used grinding media or magnetite in the ore, attaches to the magnets which over time would reduce their field strength. This complication is removed by encasing the magnets in a rubber lined stainless steel tube and periodically and automatically removing the magnet from the slurry so that the ferromagnetic material is washed back into the slurry. Even high levels of magnetite that can be found in some ores are not detrimental to the magnetic conditioning. The magnet removal from the slurry is facilitated by attaching the magnet to a compressed air piston. This is the only operating cost of the process.

Magnetic aggregation has been demonstrated in many plants world-wide on a range of sulphide minerals; copper sulphides (10) sphalerite (11), paramagnetic galena (12), pentlandite (13).

Statistical Testing in Metallurgical Plants

Metallurgists at minerals processing plants often find it difficult to implement strategies to improve production efficiencies. This is especially true where modern flotation circuits are operating at production rates higher than design. While new technologies continue to be researched and developed, it has often been problematic to scale new technologies to an industrial level and reliably prove a benefit that is meaningful for metallurgists to pursue.

Magnetic conditioning is a rare and unique physical innovation to modern flotation that can be statistically evaluated against incumbent operation. Results are real and from the plant, not modelled; offering metallurgist’s certainty before a commitment to purchase is required. Plant testing of the patented magnetic conditioning technology is a low cost and low-risk option where evaluations can be made by comparing two process conditions in a concentrator; magnetic conditioning ‘ON’ and magnetic conditioning ‘OFF’ (incumbent operation).

The most powerful plant test available, similar to testing a new reagent, is using a paired design, in which two conditions are tested as pairs in time sequence. As such, the evaluation of the data can be performed using a paired t-test (14). Analysing the plant data using the paired t-test yields a mean paired difference between magnetic conditioning ON and magnetic conditioning OFF and a level of confidence to assess whether the difference in mean results is real or due to random variation in the plant. The advantage of the paired t-test is that variability between the two conditions, such as feed conditions, plant conditions and operators are reduced increasing the power of the evaluation.

Experimental

Testing the magnetic conditioning technology in one line of Kennecott’s Cu rougher circuit was performed on an alternating 2-day magnetic conditioning ON and 2-day magnetic conditioning OFF schedule between late April and early December 2020.

Magnetic conditioning at Kennecott involved installing and commissioning eleven high-gradient rare earth magnets encased inside a rubber lined stainless steel tube spread between the first two cells of one rougher row. Installing magnetic conditioning at the front of the circuit is important to maximise the probability of magnetised particles aggregating and then increasing the aggregated minerals flotation recovery down the bank.

The technology is automatically controlled using a 24V DC PLC control system which communicates to the local cellular network where commands can be sent to program the positioning of the high-gradient rare earth magnets. As such, when magnetic conditioning is ON, each high-gradient rare earth magnet would cycle in and out of the slurry for 5 minutes (conditioning) and 1 minute (cleaning) respectively. When magnetic conditioning is OFF, each high-gradient rare earth magnet would remain at the top half of the stainless-steel tube out of the slurry to represent incumbent operation. There is no magnetic field present in the slurry when magnetic conditioning is OFF.

Kennecott has 4 parallel rougher flotation lines with each having seven 300m3 cells. Concentrate reports to the cleaning circuit and rougher tails reports to final tails. Testwork showed that while the rows were parallel, even parallel feed from the same feed splitter box was not the same. So rather than pairing the outcomes from the two rows that weren't the same, it was decided to pair consecutive days from the same row.

Results were only removed when either one or both of the ON or OFF days in the pair had a missing assay/sample or where the plant was operating at low throughput or shutdown. After refining the dataset to remove pairs with low tonnage and missing data, Grubbs' method of rejecting outliers was applied and pairs were rejected with >99% confidence as being unlikely to be a true part of the population of differences being sampled (14).

Results and Discussion

Row 7: Analysing magnetic conditioning ON and OFF in the same row

With short residence times, standard pairing techniques which adjoin days or shifts was deemed to be a suitable method for trialling magnetic conditioning in one row of Kennecott's rougher circuit.

The paired t-test is the definitive method for analysis a paired trial. Table 1 shows a summary of the results conducted for the ON-OFF pairs.

Table 1 Paired t-tests for ON-OFF differences in key processing variables.

Row 7	Tonnage (tph)	%Cu Fd	%Cu Ro Tl	%Cu Ro Rec
Magnetic Conditioning ON	1456	0.397	0.0439	88.26
Magnetic Conditioning OFF	1437	0.383	0.0474	87.14
Difference	20	0.013	-0.0034	1.12
P-value	0.751	0.432	0.045	0.033
Confidence Lvl	low	low	95.5%	96.7%

The test for differences in upstream variables of the magnetic conditioning is 2-sided as magnetic conditioning technology installed in cells 1 and 2 of Row 7 cannot influence throughput rate or feed grades. The P-value for both variables (P-value >0.05) indicates that a metallurgist should accept the null hypothesis which assumes there is no statistical difference in throughput rate or copper feed grade between the two conditions. Since upstream variables are not different between the ON and OFF conditions the confidence in reliably comparing the recovery difference over the trial period is greater. Further, the paired trial design itself, negates any daily random time-based changes such as ore-type, feed grade and mineralogy.

The difference in copper recovery is a 1-sided paired test because based on theory and outcomes elsewhere, the test aim is to measure whether there is an increase in recovery with magnetic conditioning (14).

The P-value of 0.033 which is less than the conventional value of 0.05 used to reject the null hypothesis means that a metallurgist can conclude that there is an improvement in recovery in the ON condition. The best estimate of the Cu recovery improvement during the trial is therefore, the difference in the means, which is 1.12%. Therefore, a metallurgist can be 97% confident there is a 1.12% improvement in copper rougher recovery in Row 7 with magnetic conditioning ON.

Also, a confidence interval was calculated. The importance of a confidence interval is to ensure that at a minimum, magnetic conditioning provides an economic benefit over that of incumbent operation. Using a one-tailed t-test, a metallurgist can be 90% confident that the improvement with magnetic conditioning ON in Row 7 copper rougher recovery is at least 0.35%, and could be as much as 1.89%.

A secondary comparison of the paired t-test results can be undertaken by using graphical methods. It should be appreciated that graphical analysis is less powerful, and qualitative rather than quantitative, unless the data set is extremely large. But graphical methods provide supporting evidence for the difference in recoveries shown by the paired t-test.

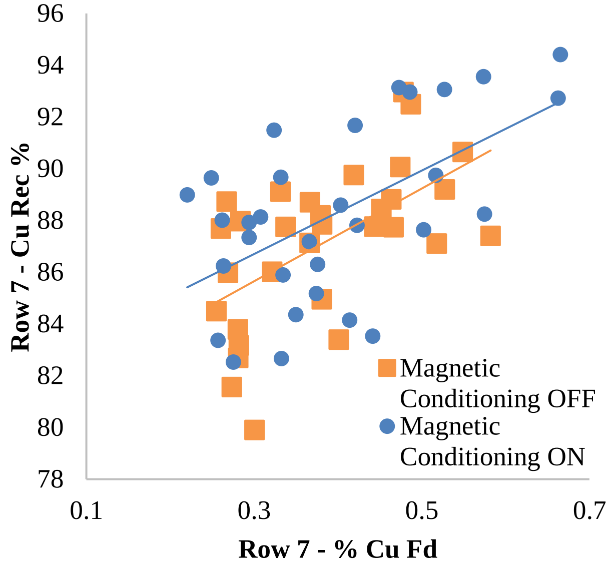

Figure 2. Row 7 %Cu rec vs %Cu fd grade for paired daily results.

Graphing copper recovery with respect to feed grade and producing a line of best fit effectively models out any effect of feed grade on recovery. Calculating the difference between the lines of best fit for both conditions at an average feed grade (0.39%) over the test duration yields a best estimate of 0.90% in copper rougher recovery with magnetic conditioning ON. The results obtained graphically are consistent to that of the preferred paired t-test output.

Row 7 and Row 8: Analysing magnetic conditioning ON in Row 7 and incumbent operation in Row 8

Kennecott's grinding circuit configuration permits a comparison between Row 7 magnetic conditioning ON and the equivalent Row 8 data as a further check on the conclusions previously made. However, comparisons across circuits have to be made with extreme caution in view of the possibility of the two flotation circuits are running under different conditions.

In this case, a paired t-test measured a significant difference between copper feed grades between the two rows. Row 7 experienced copper feed grades about 0.025% higher than Row 8 during the test period emphasising that two circuits which process the same ore from the same mill, fed from the same splitter box, are not identical. This analysis showed that the differences in copper rougher recovery measured between the two rows was a function of the difference in feed grade as well as magnetic conditioning ON in Row 7. Therefore, comparisons between Row 7 and Row 8 posed underlying limitations and hence was the non-preferred method to conclude whether magnetic conditioning improved circuit metallurgy. It should also be appreciated that during the magnetic conditioning trial, a separate froth crowder trial was running on Row 8 in the latter part of the magnetic conditioning trial.

Overall, the paired trial in Row 7 is to be preferred and thus no further analysis was conducted for the comparison between Row 7 and Row 8.

Economic Outcome:

The financial benefit to Kennecott with magnetic conditioning was large and at a low operating cost. Each additional pound of copper was produced at a cost of about $0.20/lb, well below the current LME price of $3.50/lb (October 2022). It should be appreciated that the benefit with magnetic conditioning, was demonstrated on the plant, under normal operating conditions was to high statistical confidence using the most powerful statistical method. The benefit of testing this technology on a plant scale meant that the decision for Rio Tinto to install the technology for the remaining three rougher rows posed negligible financial risk.

Rougher Circuit Roll Out

The original single row magnet conditioning equipment had been fabricated in 12 weeks, with shipping from Australia taking another 10 weeks, so installation was about 22 weeks after the decision to test was confirmed.

When the test was complete and the decision made by Kennecott management in June 2021 to proceed with installation in the other three rougher rows, COVID-19 had severely disrupted supply chains. Many countries were in lockdown, supply chains were in chaos and the vaccine roll out had just commenced. Many things in the world had changed.

Due to forward planning and the tight, communicative management by the metallurgical team that provided updates of the proposal through the approval process, the fabrication time for each of the 3 rows was similar to the fabrication time for the initial row. However, the shipping time from Australia to Utah was delayed significantly. The magnetic conditioning technology for two rougher rows were shipped, with an ETA of 8 weeks into Los Angeles but the actual duration into Los Angeles port was 5 months. The 700 miles from port to Salt Lake City, Utah took about another 2 weeks. Even to get from one side of Salt Lake City to the minesite about 30 miles away took 4 days. Total time from factory to site was more than double during Covid, compared to pre-Covid.

When the delays in shipment became apparent the final row was air freighted from Sydney to Los Angeles. Fortunately, the price of air freight from Sydney was reduced because commercial airlines were virtually empty of passengers, because of government regulation, so freight filled the empty planes. Even air freight took a month from factory to destination. This led to a cost increase for the project, but it was small relative to the benefit in increased copper.

Along with the extended delivery times was a continuously changing and unreliable delivery date. The changing delivery date meant scheduling the installation and mobilising contractors for the installation became a serious management problem. This was compounded by the extra restrictions around COVID-19. Installation dates changed multiple times, which was a management headache. Nevertheless, despite the Covid induced complications the installation was successful and with no safety incidents.

Conclusions

A statistical plant test of magnetic conditioning over about 8 months at Rio Tinto's Kennecott Copper mine showed a 1.12% increase in copper recovery to high statistical confidence. The resulting economic benefit to the operation is substantial and results in a lower average cost of production per lb of copper produced.

The subsequent installation in the total rougher circuit was disrupted and delayed significantly because of the chaos in world supply chains caused by COVID-19. Nevertheless, the total installation occurred in a reasonable time frame and with no safety incidents.

Acknowledgements

Barry and Christos would like to thank the Kennecott metallurgical team for their support and professionalism in the undertaking of the project. Ausmetec would like to thank Kennecott for their permission to publish the paper.

References

1. Cononelos, L.J. (1994), A brief history of change and leadership challenges at Kennecott. Internal Kennecott document.

2. "Rio Tinto's Kennecott wins clean air lawsuit in the US | MINING.com". *MINING.com*. June 9, 2016. Retrieved June 16, 2022.

3. Duan, J. Fornasario, D. and Ralston, J. (2003), Calculations on the flotation rate constant of chalcopyrite particles in an ore. *Inter. J. Miner. Process.*, 71, 227-237.

4. Ahmed, N. and Jameson, G. (1985). The effect of bubble size on the rate of flotation of fine particles. *Inter. J. Miner. Process.* 14:196-215.

5. Holder, R, 1994. Improvement in copper and silver flotation at Hellyer using high energy conditioning. , *in Proceedings of the Fifth Mill Operators' Conference*, pp 153-159 (The Australasian Institute of Mining and Metallurgy: Melbourne).

6. Song, S, Lopez-Valdivieso, A, Reyes-Bahena, J and Lara-Valenzuela, C, 2001. Floc- flotation of galena and sphalerite fines, *Min Eng*, 14(1):87-98.

7. Svoboda, J. (1987), *Magnetic Methods for the Treatment of Minerals*, (Elsevier: Amsterdam).

8. Gaudin, A. and Rush Spedden, H. (1943), Magnetic separation of sulphide minerals, *AIME Transactions*, 153:563-575 (American Institute of Mining and Metallurgical Engineers Inc).

9. Wilding, J, and Lumsden, B. (2012), Implementation of magnetic conditioning in two stage sequential Cu-Zn flotation separation, in *Proceedings of the Conference of Metallurgists,* pp139-148, (Metallurgy and Materials Society: Quebec).

10. Rivett, T. Wood, G. and Lumsden, B. (2007), Improving fine Cu and Au flotation recovery – a plant evaluation, in *Proceedings of the Ninth Mill Operators' Conference*, pp 223-228 (The Australasian Institute of Mining and Metallurgy: Melbourne).

11. Lacouture, B. Wilson, B. Oliver, J. and Lumsden B. (2016), Improving fine sulphide mineral recovery at the red dog operation IMPC 2016.

12. Holloway, B. Clarke, G. and Lumsden, B. (2008), Improving fine lead and silver flotation recovery at BHP-Billiton's Cannington mine, *in Proceedings of the 40th Annual Meeting of the Canadian Mineral Processors 2008,* pp 347-362 (Canadian Institute of Mining, Metallurgy and Petroleum)

13. Musuku, B. Muzinda, I. and Lumsden, B. (2015), Cu-Ni processing improvements at First Quantum's Kevitsa mine, *Min. Eng.*, 88: 9-17.

14. Napier-Munn, T. (2010), Designing and analysing plant trials, in: Greet, C. (Ed.), Flotation Plant Optimization. The Australian Institute of Mining and Metallurgy, Melbourne, pp. 175-190.