

Testing Magnetic Conditioning at Escondida's Laguna Seca Concentrator

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ABSTRACT

Escondida has long held the title of the world's leading copper mine, consistently producing over 1 million metric tons of copper annually — a figure unmatched by any other mine for nearly three decades. The mine plays a crucial role in Chile's economy, contributing approximately 2.5% to the nation's GDP — a remarkable impact for a single mining operation.

The process plant feed at Escondida is a complex blend of copper sulfides, with chalcocite and chalcopyrite being the predominant copper bearing minerals. However, the ratio of these sulfides can vary significantly across the ore body. To maintain planned levels of copper output, Escondida's process development and operations team works tirelessly to maximize production efficiency while also exploring new processing technologies that can be adapted to optimize copper extraction from the ore.

Magnetic conditioning has been successfully plant-tested and introduced at some of the largest base metal sulfide flotation plants, demonstrating an increase in metal recovery and grade. The technology leverages the paramagnetic properties of copper sulfides and their ability to aggregate when magnetized. Since copper sulfides of typically less than 10 microns have poor flotation efficiency, aggregating these minerals increases their size, momentum, and flotation performance.

At Escondida, the copper sulfides were measured to be paramagnetic, and copper losses in the fine and middling fractions were significant. Therefore, magnetic conditioning was identified as a suitable technology and was tested in the rougher and cleaner flotation circuits in the Laguna Seca Line 2 concentrator for five months, starting in December 2023. The plant experiment was a statistically based ON/OFF paired test, using plant automatic samplers to define potential increases in copper circuit recoveries.

In the copper rougher flotation circuit, magnetic conditioning increased copper recovery by 0.8%, to high statistical confidence. In the copper cleaner flotation circuit, in which much finer particles are processed, there was a 0.5% increase in copper recovery, also to high statistical confidence. This resulted in a combined 1.2% increase in global copper recovery.

INTRODUCTION

The Escondida Mine, located in the Atacama Desert approximately 170 km southeast of Antofagasta, Chile, is the world's largest copper-producing mine and is classified as a porphyry copper deposit. It is operated and majority-owned by BHP Ltd (57.5%), with Rio Tinto (30%) and JECO Corporation (12.5%) holding minority interests. The mine operates three concentrators—Los Colorados, Laguna Seca 1, and Laguna Seca 2—processing ore from two open pits, with Laguna Seca 2 being the newest and largest of the three plants.

Even though the Laguna Seca 2 Concentrator operates at a relatively coarse grind (160–180 microns), typical of large-scale porphyry operations, data from January - December 2023 (as per Figure 1 and 2) shows a significantly high concentration of copper present in the <11-micron size fraction of both the rougher and cleaner scavenger tailings—streams that ultimately report to final tailings.

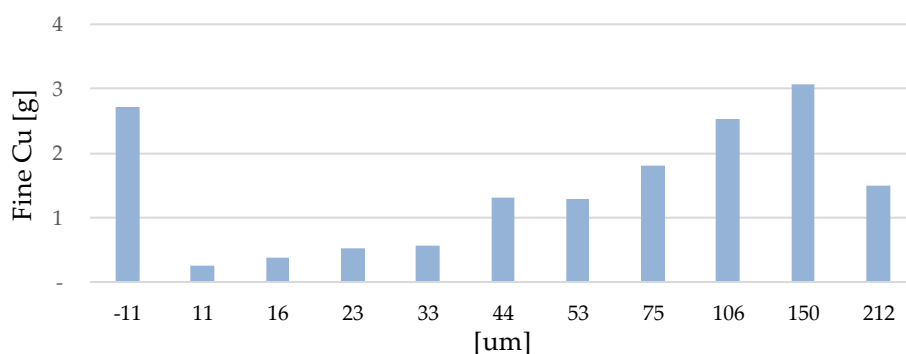


Figure 1 Average copper mass in rougher tailings from Laguna Seca 2 in January – December 2023

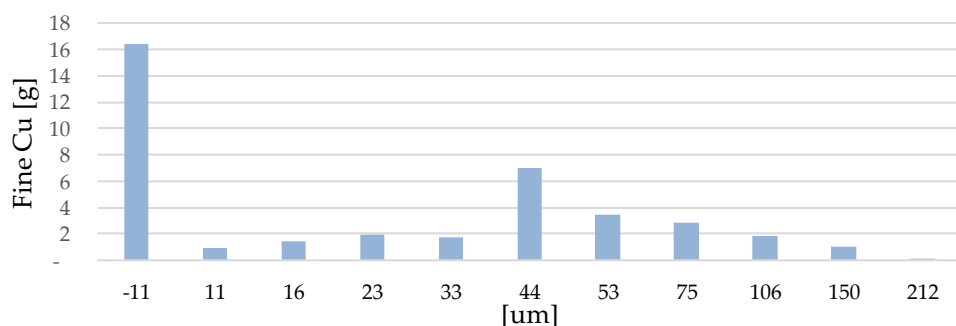


Figure 2 Average copper mass in cleaner tailings from Laguna Seca 2 in January – December 2023

Figures 1 and 2 show that approximately 30% of the copper lost to rougher tailings is in the $<38\ \mu\text{m}$ size fraction, with 20% in the $<11\ \mu\text{m}$ range. Similarly, around 70% of the copper lost to cleaner-scavenger tailings is $<38\ \mu\text{m}$, with 50% occurring in the $<11\ \mu\text{m}$ fraction. These losses highlight the well-known challenges associated with recovering fine particles in conventional flotation cells, as fines tend to have lower collision efficiency with air bubbles, leading to reduced overall recovery.

Fine Mineral Recovery

The relationship between particle size and flotation recovery was first identified by Gaudin, Groh and Hendersen (1931), who demonstrated that both fine and coarse particles exhibit poor recovery to the froth phase. In particular, the low recovery of fine sulfide minerals (typically $<20\ \mu\text{m}$) has been attributed to their poor collision efficiency with air bubbles, a result of their small mass and correspondingly low momentum (Duan et al., 2003).

Although sulfide flotation remains the dominant route for copper production, the challenge of recovering fine particles—first recognized nearly a century ago—persists today. In fact, the issue has become more pronounced, driven by declining ore grades, increasingly fine-grained ores, and the need for finer grinding to maintain mineral liberation and selectivity. While various technologies have been developed to enhance coarse particle flotation (Jameson and Emer, 2019), the effective and selective recovery of fine particles remains one of the most significant challenges in modern flotation practice.

Several approaches have been investigated to improve fine particle recovery in flotation. Increasing the hydrodynamic energy to boost particle velocity—and hence momentum—has been shown to enhance fine particle-bubble collision. However, this approach lacks selectivity and can negatively impact coarse particle recovery (Ahmed and Jameson, 1985; 1989). Similarly, reducing bubble size can improve collision probability with fine particles but again, this strategy does not offer selective recovery (Finch and Dobby, 1990).

An alternative and potentially more selective approach involves increasing the mass of fine particles through agglomeration techniques, thereby enhancing their momentum and collision efficiency. However, to date, most agglomeration strategies have proven to be either non-selective or cost-prohibitive. Notably, only magnetic conditioning-induced agglomeration has been demonstrated at plant scale to be both selective and economically viable (Engelhardt, et al., 2005; Rivett, et al., 2007; Wilding and Lumsden, 2011; Manouchehri, 2014; Lacouture et al., 2016).

Magnetic Susceptibility of Sulfide Minerals

Many of the sulfide minerals recovered by flotation exhibit paramagnetic properties. Early work by Gaudin and Rush-Spedden, (1943) demonstrated that minerals such as chalcopyrite, bornite, chalcocite, and sphalerite are paramagnetic. While ferromagnetism has long played a critical role in mineral processing—particularly in magnetic separation—paramagnetic minerals are typically too weakly magnetic to be recovered efficiently using conventional magnetic separators.

For several decades, the paramagnetism of sulfide minerals was considered to have limited practical relevance. However, this changed with the discovery that paramagnetic sulfides, although not directly separable by commercial magnets, can be selectively magnetized and induced to form aggregates under the influence of a magnetic field (Svoboda, 1987). This selective magnetic aggregation technique increases the effective mass and thereby improving the momentum of fine particles.

While the magnetic susceptibilities of sulfide minerals are well-documented in the literature (Svoboda, 1987), studies have shown significant variability depending on orebody and mineral composition. Gaudin and Rush-Spedden, (1943) noted that the magnetic response of specific sulfides can vary depending on the geological source and mineralogical compositions. More recent investigations have identified cases where minerals traditionally classified as diamagnetic, such as galena or molybdenite, exhibit paramagnetic behaviour (Holloway et al., 2008; Medina et al., 2022). This variability is believed to result from isomorphic substitution—such as iron substituting for other metals—and trace elemental contamination within the sulfide crystal lattice.

At Escondida, five final copper concentrate samples (~100–200 g each), collected over various time periods, were sent to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia for magnetic susceptibility testing. CSIRO is a government research agency with expertise in applied mineralogy and materials characterization. Table 1 provides the magnetic susceptibility of the concentrate sample and the copper minerals.

Table 1 Magnetic susceptibility results from Escondida samples (reproduced from CSIRO, 2025)

Sample	Proportion of Cu Sulfides in Sample %	Cp:Cc Ratio	Magnetic Susceptibility of Cu Minerals $\times 10^{-9} \text{m}^3 \text{kg}^{-1}$
1	48	0.50	1054
2	46	0.39	1660
3	45	0.45	2744
4	48	0.32	2740
5	56	2.19	1201
Chalcopyrite (Svoboda, 1987)	100	-	1596

Further testwork was conducted by combining Samples 1 and 2, and Samples 3 and 4, to form two composite samples, which were then processed through a Franz magnetic separator. The samples were combined as they were collected during similar operational periods. Sample 5 mineralogical analysis was not undertaken at the time of collection, so later analysis would have been compromised. Table 2 provides the weight distribution of each sample at varying amperages, from ferromagnetic to non-magnetic mass.

Table 2 Mineral separation testwork with Franz magnetic separator (reproduced from Geotrack Mineral Services Pty Ltd, 2025)

Sample	Weight Distribution %			
	Ferro magnetics	0.5A magnetics	1.5A magnetics	1.5A non-magnetics
1 & 2	0.01	90.25	7.56	1.85
3 & 4	0.001	94.64	4.75	0.22

The magnetic fractions collected at 0.5 A (strongly paramagnetic) and 1.5 A (weakly paramagnetic) captured >98% of the total sample mass and were submitted for optical mineralogical analysis to evaluate the distribution of copper-bearing minerals both in each fraction and between fractions. Results are provided in Table 3 and Table 4, respectively.

Table 3 Distribution (%) of copper sulfides in each of the 0.5 A and 1.5 A magnetic fractions (reproduced from MODA microscopy, 2025)

	0.5A magnetics		1.5A magnetics	
	Sample 1 & 2	Sample 3 &4	Sample 1 & 2	Sample 3 &4
Chalcopyrite, Cp	17.1	14.9	16.6	6.9
Chalcocite, Cc	75.5	76.7	75.8	89.2
Covellite, Cv	5.2	6.5	6.8	3.3
Other	2.2	1.9	0.8	0.6
Total	100	100	100	100

Table 4 Distribution of copper sulfides between the 0.5 A and 1.5 A magnetic fractions (reproduced from MODA microscopy, 2025)

	Sample 1 & 2			Sample 3 &4		
	0.5A magnetics	1.5A magnetics	Total	0.5A magnetics	1.5A magnetics	Total
Chalcopyrite, Cp	93.7	6.3	100	98.7	1.3	100
Chalcocite, Cc	93.5	6.5	100	96.9	3.1	100
Covellite, Cv	91.8	8.2	100	98.6	1.4	100

The optical mineralogy shows that the predominant sulfide is chalcocite, while chalcopyrite content is a minority and the covellite content is low. Chalcocite and covellite are generally reported in the literature as diamagnetic and chalcopyrite as strongly paramagnetic (Pearce et al., 2006). However, for Escondida, the chalcocite and covellite are strongly paramagnetic, with >90% reporting to the strongly paramagnetic fraction. This finding that chalcocite is strongly paramagnetic is consistent with the study by Gaudin and Rush-Spedden (1943); however, the authors found covellite to be weakly paramagnetic, whereas, the Escondida testwork has shown covellite to be strongly paramagnetic.

The results from Table 3 and Table 4 demonstrate that Escondida's predominant copper sulfide minerals are strongly paramagnetic since negligible mass of concentrate reports to the 1.5A magnetic fraction. Despite the varying magnetic susceptibility results of samples 1-5, the data suggests that Escondida's complex blend of copper minerals would suit very well to magnetic conditioning.

Magnetic Conditioning

Chemical conditioning and aeration are commonly used methods to treat flotation slurry prior to flotation, with the aim of optimizing slurry conditions for maximum separation efficiency. These are pre-flotation treatments, not part of the flotation process itself, but are critical in preparing the slurry for improved performance. Similarly, magnetic conditioning is a pre-treatment process, designed to enhance flotation recovery. Unlike chemical or aeration conditioning, magnetic conditioning involves exposing the slurry to intense magnetic fields to magnetize paramagnetic sulfide minerals within the pulp, allowing magnetic aggregation to occur.

A key component of this process is the use of modern rare-earth permanent magnets, which generate high-strength, high-gradient magnetic fields—currently the strongest available at room temperature from non-electromagnetic sources. Although these magnets are relatively expensive, their magnetic intensity, stability, and durability make them well-suited for magnetic conditioning applications.

When paramagnetic minerals are magnetized in the slurry and come into close proximity, they naturally agglomerate, much like two magnets attracting one another. This agglomeration increases the effective mass of fine particles.

Contrastingly, gangue minerals, like quartz, the main diluent in flotation concentrates, are diamagnetic and so unaffected by the magnetic conditioning. This increases the selective flotation of the paramagnetic sulfides. Pyrite, another diluent mineral is also reported to have a very low magnetic susceptibility and so is also unaffected by the magnetic conditioning stage (Svoboda, 1987).

Plant experimentation has shown that if two different paramagnetic sulfide minerals are in the slurry, they do not heterogeneously agglomerate but homogeneously agglomerate. Several studies have shown that magnetic conditioning improves the separation of two paramagnetic minerals,

chalcopyrite - sphalerite separation by sequential flotation (Wilding and Lumsden, 2011). This supports the hypothesis that the magnetic agglomeration is homogeneous.

METHODOLOGY

Significance of the Paired t-test

The paired *t*-test is considered one of the most powerful statistical methods for evaluating process changes under ON and OFF conditions (Napier-Munn, 2010). This approach relies on a sequential or randomized ON/OFF schedule, where adjacent time periods—typically a shift or a day—are paired, and the differences between each pair are statistically analyzed. The strength of the short period pairing method lies in its ability to reduce plant variability between ON and OFF states. Since adjacent periods are more likely to be similar in terms of operational conditions and ore characteristics, unlike comparing periods separated by time, where ore and operational differences are likely greater. Daily or shift pairing also maximizes data collection, an important consideration in plant testing and evaluation.

Effective paired testing in an industrial flotation circuit requires reliable automatic sampling, along with rigorous sample preparation and assaying protocols. In the context of magnetic conditioning, which primarily targets fine mineral particles, analyzing the assay and metal distribution by size of key streams—particularly focusing on changes in the <25 micron fraction—can provide valuable insights into process performance.

Plant Testing

ON/OFF testing at Escondida was conducted over a five-month period in one row of the rougher (Line 1) and cleaner scavenger circuit (Line 8, 9 and 10) of the Laguna Seca 2 Concentrator. Due to the short residence times in the rougher flotation circuit, a 1-day ON/OFF schedule for magnetic aggregation was implemented, with adjacent 12-hour shifts designated as either ON or OFF and paired. In contrast, the cleaner flotation circuit - characterized by significant recirculating loads - was tested using a 2-day ON (4 shifts) and 2-day OFF (4 shifts) schedule. This approach follows recommendations by Napier-Munn (2010), who suggests that circuits with recirculating loads may require a full period to reach equilibrium, meaning the performance on the day of the schedule change should be disregarded. Statistical analysis of the cleaner flotation circuit trial was evaluated on a shift-by-shift basis to understand the effect on recirculating loads.

A fully automated control system with remote reporting capabilities was employed to switch magnetic conditioning ON and OFF at 7:00 AM. This timing coincided with sample collection for laboratory analysis. Notably, the process required no operator intervention, ensuring consistent execution of the testing schedule.

Data was refined based on removing low tonnage pairs, missing data and outliers using the Grubbs outlier test (Napier-Munn, 2010). These steps to refine the data are widely acceptable when

analysing plant trials to ensure the data set captures ‘normal operation.’ No other filters were applied to the data which illustrates the robustness of the result and in turn provides confidence in the results presented.

RESULTS AND DISCUSSION

Rougher Flotation Circuit Evaluation

Table 5 illustrates the paired t-test output of key variables in rougher flotation circuit (Line 1) of the Laguna Seca 2 Concentrator.

Table 5 Paired t-test results with magnetic conditioning ON and OFF in the rougher flotation circuit

Rougher Flotation Line 1	Ro Rec %Cu	>25µm Ro Rec %Cu	<25µm Ro Rec %Cu
Incremental Difference (ON-OFF)	0.80	0.59	0.57
Confidence Level %	98	87	98

While upstream variables like tonnage, P80 and feed grade are confidential, it should be noted that these upstream variables, as expected, did not show any statistical difference between magnetic conditioning ON/OFF. This made analysis of downstream variables impacted by magnetic conditioning ON and OFF straightforward and reliable.

The statistical test for differences in downstream variables like recovery was a 1-sided paired t-test. Magnetic conditioning ON increased incumbent copper rougher recovery by 0.80% to 98% statistical confidence (p-value = 0.02). Sizing results are consistent to the improvement measured by using the plant data.

It is interesting to note that magnetic conditioning ON, increased the copper rougher recovery in the coarse (>25um) fraction but not to >90% statistical confidence. Nevertheless, it was similar in magnitude to the increase in the fine (<25um) fraction. This is consistent and confirmatory with recent industrial testwork from other mines that have been published; Constancia (Medina et al., 2022), Aguas Teñidas (Bermejo et al., 2024), and others that are not published. This is due to the technological advancement of the permanent magnets used. The explanation for this may be that magnetic conditioning not only increases the probability of recovery for fully liberated fine copper particles but also partially locked coarser minerals too. While it is not possible to ascertain the exact size fraction which magnetic conditioning targets in the coarse (>25um) fraction, it is likely to be the middling’s fraction in the range of 75-25 microns. It is important to appreciate that if there is raw exposure on the surface of a copper bearing composite mineral despite it being partially locked by gangue, these copper minerals can still become magnetized and have the potential to agglomerate with another magnetized copper mineral. While the probability of recovery and agglomeration for

a partially locked copper mineral that has been magnetized is lower than the probability of fully liberated magnetized particles agglomerating and being recovered, this phenomenon occurs based on the sizing results obtained at Escondida (Table 5).

Cleaner Flotation Circuit Evaluation

Table 6 and Table 7 details the paired t-test output of key variables in cleaner flotation circuit of the Laguna Seca 2 Concentrator.

Table 6 Paired t-test results with magnetic conditioning ON and OFF in the cleaner flotation circuit

Cleaner Flotation Cu Rec	1 st shift	2 nd shift	3 rd shift	4 th shift
Incremental Difference (ON-OFF)	0.20	0.00	0.26	0.50
Confidence Level %	low	low	low	95

Table 7 Paired t-test results of key variables when comparing the 4th shift with magnetic conditioning ON and OFF

Cleaner Flotation Circuit 4 th shift ON/OFF	Cl Rec %Cu	Final Conc %Cu	>25µm Cl Rec %Cu*	<25µm Cl Rec %Cu*
Incremental Difference (ON-OFF)	0.50	0.03	0.53	1.23
Confidence Level %	95	low	low	98

*Sizing data for the cleaner flotation circuit ended prematurely due to overload in samples to the lab and so the results presented represent half of the testing period.

Evaluating a change in cleaner flotation circuits, particularly to measure the behavior of fine minerals, can be complex to analyze since recirculating loads can make it difficult to know how the circuit truly behaves. Therefore, to provide flexibility with pairing techniques, a 2-day magnetic aggregation ON and OFF test schedule was programmed.

In the case for the cleaner flotation circuit at the Laguna Seca 2 Concentrator, the data suggests that there are significant re-circulating loads of fine copper-bearing particles. It took three shifts for a positive and statistically significant effect with magnetic conditioning to occur. This is not a surprising observation. The fine copper-bearing particles targeted by magnetic conditioning is the slowest floating particles and so most likely to be the mineral recirculating in the cleaner flotation circuit. This time-delayed effect on the recovery of fine copper-bearing particles pre-treated with magnetic conditioning has been reported in the literature (Medina et al., 2022; Lacouture et al., 2016) and observed in other plants, although not formally published. The benefit observed in the 4th shift ON/OFF period show a 0.50% increase in cleaner flotation copper recovery (to 95% statistical confidence) with no detrimental effect to final copper concentrate grade – owing to the selectivity of

magnetic conditioning. Size-by-size assay data, is highly consistent with the overall cleaner flotation circuit recovery improvement, as a 1.23% increase in <25µm cleaner flotation circuit recovery was measured to 98% statistical confidence.

Table 6 also indicates that there could be a further increase in copper cleaner flotation recovery on the 5th and 6th shift; so that the 0.50% increase in cleaner copper recovery should be seen as a minimum benefit. However, due to ore and operational variability, extending the ON and OFF periods is not preferred. A longer timeframe, such as a 3-day (6-shift) ON/OFF test schedule, can amplify circuit variability, potentially obscuring the benefits of magnetic conditioning and making errors more difficult to control (Napier-Munn, 2010).

CONCLUSION

A comprehensive study was conducted to define the effect of magnetic pre-conditioning of sulfide ore at Escondida's Laguna Seca copper rougher and cleaner flotation circuits. A five-month industrial ON/OFF paired t-test with magnetic conditioning resulted in statistically significant increases in copper recovery of 0.8% in the rougher flotation circuit and 0.5% in the cleaner flotation circuit. When combined, these improvements correspond to a 1.2% increase in overall plant recovery. As a result, the magnetic conditioning units used during the trial were left operating continuously to capture the ongoing benefit. Given the substantial improvement in copper recovery, Escondida has initiated the fast-tracked deployment of magnetic conditioning across the remaining rougher lines at the Laguna Seca 2 Concentrator. Full implementation is also being pursued at both the Laguna Seca 1 and Los Colorados Concentrators, supported by the similar mineralogy and processing conditions shared among the three plants.

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NOMENCLATURE

A	amperage
Cp	chalcopyrite
Cc	chalcocite
Cc	covellite
g	gram

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