REDUCING THE LOSS OF <12 μm COPPER TO TAILINGS

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ABSTRACT

The Phu Kham Cu-Au mine in Laos is owned and operated by Phu Bia Mining Limited. The deposit is a complex and low grade Cu-Au porphyry ore. The rougher feed has a particle size distribution of 80% passing 110 μm, and the rougher concentrate is reground for cleaning to 80% passing 25 μm. The Cu losses in the cleaning circuit are primarily in the <12 μm fraction. A randomised paired ON-OFF test of magnetic conditioning in one of the two parallel cleaner 1 circuits was undertaken. The results showed that with magnetic conditioning there was approximately a 10% reduction in the <12 μm Cu distribution in the cleaner 1 tail to a 98% level of confidence. The Cu distribution in the <12μm fraction is a less variable measure of changes in the <12μm Cu recovery, therefore, this was used to evaluate the impact of magnetic conditioning.

Subsequently, magnetic conditioning was installed in both cleaner 1 circuits and the plant results monitored after this installation. Comparing the plant results immediately before and after this installation showed that there was a 20% reduction in <12μm Cu losses to the cleaner tail.

INTRODUCTION

The Cu-Au, Phu Kham Operation (PKO) is located within PanAust's Phu Bia Mining Contract Area in Laos, approximately 140 kilometres from the capital city, Vientiane. PKO is PanAust's flagship operation and the significant cash flow generated by PKO has supported PanAust's growth, while contributing to a strong balance sheet.

PKO comprises an open-pit mine and a conventional milling and flotation operation that produces and exports a Cu and precious metals concentrate. The concentrate contains around 23% Cu, 6 ppm Au and up to 35 ppm silver.

Process Overview

The PKO deposit consists of complex heterogeneous mineralogy horizons of Cu-Au stockwork and skarn mineralisation. It contains areas of soft-leached zones, overlying transition zones and supergene chalcocite dominant secondary Cu mineralisation and clay-rich gangue. Areas of high As and Zn also pose a challenge in treating the highly variable ore. In addition, hardness of the ore increases with deposit depth.

The ROM is hauled to a primary gyratory crusher to produce a coarse ore stockpile with size distribution suitable for the 13 MW semi-autogenous mill.

The SAG product feeds two parallel ball mills each equipped with a cyclone cluster producing a product particle size distribution of 80% passing 110 μm.

The conventional flotation circuit consists of two parallel rougher banks. The rougher concentrates feed the regrind cyclone where the underflow is split and reports to two parallel, 3MW, M10000 IsaMills. The regrind mill discharge combines with the regrind cyclone overflow with a product particle size distribution 80% passing 25 µm and reports to the Jameson cell.

The Jameson cell, the first stage of concentrate cleaning, recovers the fast floating, liberated Cu sulphides and its concentrate reports to final concentrate. The Jameson cell tails is split equally and feeds the two parallel cleaner 1 circuits; the first stage of a three stage mechanical cleaning circuit.

The cleaner 1 tail is discharged to final tail and the cleaner 1 concentrates combined to feed a two stage cleaning circuit. This cleaner concentrate is combined with the Jameson concentrate and is final concentrate.

The final concentrate is thickened and filtered to approximately 9.5% moisture.

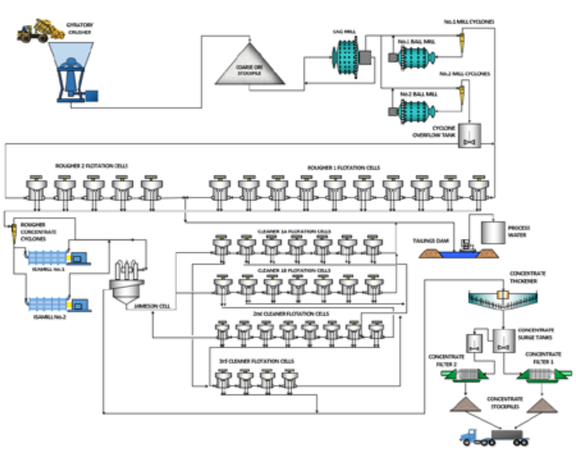

FIGURE 1 Current PKO flowsheet

Process Upgrade and Development

The development of the current PKO flow sheet from the originally designed 12 Mt/yr flow sheet has been published (1, 2). A diagram of the current flowsheet is in Figure 1.

PKO was commissioned in April 2008 and further studies were conducted to improve plant performance and increase capacity. In September 2009, flotation capacity was increased by retrofitting flotation mechanisms in the original conditioning tanks of the rougher and first cleaner circuits. In January 2011, a 10^{th} $200m^3$ flotation tank was installed in the rougher circuit and in June 2011 the Float Force mechanism installed. To accommodate the increased rougher concentrate production a Jameson cell was installed ahead of the cleaner circuit in March 2011.

Milling capacity was increased in 2012 with the installation of an additional 13 MW ball mill, and flotation capacity increased with five 200 m^3 rougher flotation cells and four 20 m^3 third cleaner flotation cells installed.

The monthly mineralogy results, showing the liberation and kinetics of Cu sulphide flotation assisted in the design of the upgraded cleaner circuit. This led to the Increased Recovery Project (IRP) which included the installation of an additional 3 MW M10000 IsaMill and the second, parallel first cleaner flotation circuit (Cleaner 1B), comprising seven 70 m^3 cells. A forty plate frame filter press was also installed

The performance of the flotation circuit is monitored by cameras that provide live feed on selected sections of the plant; as well froth cameras provide visuals on the actual condition of the froth quality and pull-out velocity. On-stream analysers also assay various process streams to monitor the plant performance.

Historical plant performance with plant changes is shown in Figure 2.

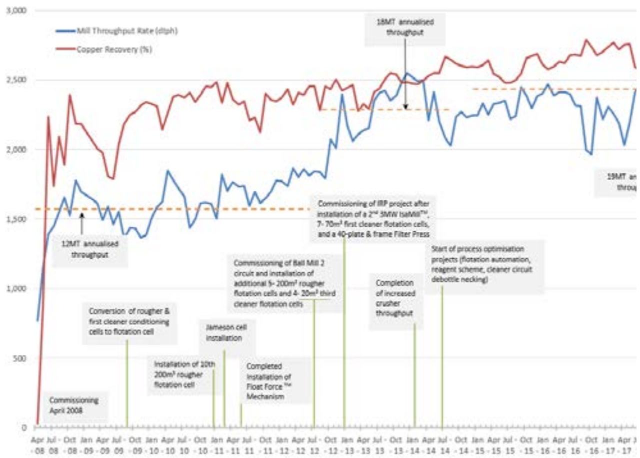

FIGURE 2 PKO development milestones with throughput and Cu recovery performance

Opportunities for Improvement

Figure 2 shows that the upgrades and modifications made in the process flowsheet substantially improved plant performance. The main challenge currently is identifying opportunities for continuous, low cost, low capital improvements. The major opportunities are focused on maintaining productivity as the ore became harder and feed grades decreased.

Weekly composite sizing of rougher and cleaner streams show that the majority of the Cu losses in the roughers occur in the coarse fractions, while the majority of the Cu losses in the cleaners occur in the fine fractions.

The operating philosophy set out in the IRP is for a 20% mass pull from the rougher circuit. The increase in the available power in the regrind circuit allows liberation of the Cu sulphides for cleaning and upgrade. Figure 3, from Chan (3), shows the Cu liberation in the cleaner tails. The cleaner tails losses account for at least 5% of the total Cu in the ore, with the liberated Cu sulphides accounting for roughly 50% of the cleaner Cu losses.

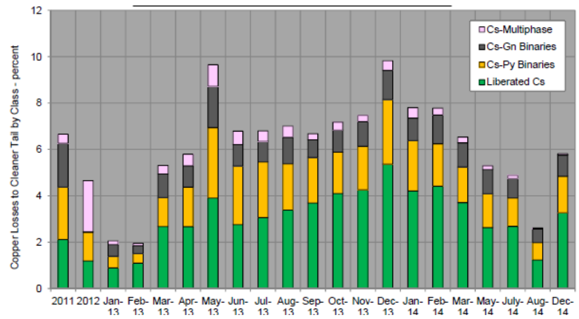

FIGURE 3 Trend of Cu loss distribution to cleaner tailings by class from mineralogical analysis

Figure 4, reveals that as expected, the 12 µm (–C5) fraction is more than 60% of the losses of liberated Cu sulphide minerals. The proportion of 12 µm liberated minerals lost does not vary markedly with changes in the feed size to the cleaners, indicating that it is unlikely that the losses of liberated particles in the 12 µm fraction is caused by over grinding in the regrind circuit. This conclusion served as the basis to investigate magnetic conditioning that selectively aggregates the 12 µm liberated paramagnetic Cu sulphides to improve their flotation recovery in the cleaner circuit.

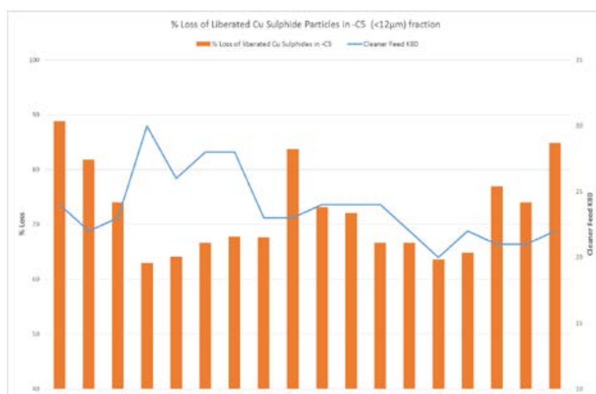

FIGURE 4 Percent loss of liberated Cu in the –C5 fraction of cleaner tailings

Fine Mineral Recovery

Flotation is very efficient at selectively recovering the mid-range size minerals. However, its efficiency deteriorates as the mineral's size moves above and below the optimum particle size envelope. For example the zinc recovery by size at the Golden Grove mine shown in Figure 5 (4).The optimum recovery envelope for sphalerite in this circuit was in the range 24 µm to 106 µm. To improve flotation efficiency and the economics of mineral processing, therefore, this less efficient mineral separation by size must be addressed.

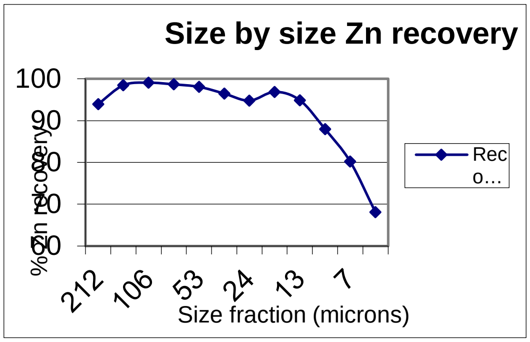

FIGURE 5 Zinc flotation recovery by size at Golden Grove

The poor flotation recovery of fine <20 µm minerals has been extensively investigated. Numerous studies demonstrated this phenomenon (5-8) and led to the conclusion that the poorer recovery of fine minerals by flotation was due to the poor collision efficiency of the mineral with the bubble.

Suggested solutions have been, reduce the bubble size or increase mineral momentum (8). But this study and similar studies demonstrated that reducing bubble size or increasing mineral momentum by increasing mineral velocity in the slurry, reduces the flotation selectivity and selective flotation is the objective.

Alternatively, increasing mineral momentum, by increasing mineral mass can be achieved by aggregating smaller minerals into larger mineral aggregates. The increase in mineral size by aggregation must be both selective and cost effective. But historically, no method has met these selectivity and cost requirements, therefore, none has been widely installed.

Magnetic Aggregation

One practical method applied in flotation plants for about a decade, that has proven both cost effective and selective, is magnetic conditioning of flotation feed (4, 9-14). The technology is based on the mineral's physical properties, rather than its chemical properties. The physical property targeted is the magnetic susceptibility of paramagnetic minerals. These paramagnetic metal sulphides include bornite and chalcopyrite, the iron-Cu minerals, as well as the silver mineral freibergite. Moreover, some naturally occurring sulphides, formed in an iron rich environment, have iron impurities in the mineral that impart a paramagnetic susceptibility to the mineral. These natural paramagnetic sulphide minerals include chalcocite (15), sphalerite (16) pentlandite (14) and galena (9).

Equally important is that the detrimental concentrate diluents, particularly pyrite and non-sulphide gangue are not paramagnetic (16).

Laboratory studies of magnetic aggregation of paramagnetic minerals have been widely published and the results are thoroughly reviewed (16). Magnetic aggregation of paramagnetic minerals is dependent on the magnetic field strength, the mineral size, the magnetic susceptibility of the mineral and the electrostatic properties of the mineral (16).

While the initial experiments were carried out on non-sulphide hydrophilic minerals like haematite, a later study showed that hydrophobic paramagnetic minerals would aggregate more readily than hydrophilic minerals (17). In summary, Svoboda (16) showed that <5 µm paramagnetic minerals of similar magnetic susceptibility to chalcopyrite will aggregate in magnetic fields strengths now possible with rare earth magnets.

Many published studies demonstrate improved flotation of <12 µm paramagnetic sulphide minerals after magnetic conditioning (4, 9-14). Statistical plant testing shows that magnetic conditioning can reduce paramagnetic mineral tail losses by 10% or more, at the same concentrate grade. The plant results are demonstrated by undertaking full scale detailed ON-OFF statistical experiments in live plants, during normal operation, using automatic plant samples. Considering, that normal plant operation involves significant variability, these statistical tests take months, with many pairs of data collected. The length of the statistical test depends on the variability (noise) in the plant, the concentration of fines in the tail stream and the experimental methodology employed.

Importantly, plant testwork has shown enhanced selectivity between two paramagnetic minerals floated sequentially: like chalcopyrite from sphalerite (13), or chalcopyrite from pentlandite (11), or galena from sphalerite (10). These results show that magnetic aggregation is homogeneous aggregation and leads not only to increases in recovery but also reductions in entrainment of paramagnetic minerals,

EXPERIMENTAL

Part 1 ON-OFF Statistical Test Experimental Methodology

Magnetic aggregation will occur provided a magnetic field of sufficient magnitude is applied to a paramagnetic mineral of sufficient magnetic susceptibility. Aggregated fine minerals will have more momentum and therefore, recover more efficiently, but detecting the effect in a variable plant is challenging. Flotation in some plants, because of their ore variability, (sulphide minerals, gangue minerals, ore hardness, degree of oxidation etc) or operational variability, produce extremely variable results. At PKO the ore from day to day is very variable. On a day to day basis Cu recovery can vary by 10% or more, Cu feed grade by 50% or more and Cu mineralogy to vary by 50% or more. Therefore, measuring a small change in mineral circuit performance to high confidence is extremely challenging. Extreme variability has meant that statistically proving financially beneficial changes in the plant has been impossible.

Paired t test statistical testing is the most powerful methodology because it removes some of the ore variability noise (18). This was the first part of the testing at PKO and statistically proved the flotation benefit with magnetic conditioning.

However, PKO are one of the few plants that do very detailed weekly sizing of their process streams on a continual basis. The second part of the magnetic conditioning evaluation process was to measure the difference in size distribution in the cleaner circuit before and after the magnetic conditioning was installed on a permanent basis. This very detailed comparison of before and after is susceptible to bias because there may be a step change or ongoing change in ore or other plant processes coincident with the process change. Therefore, caution was required when analysing these before and after results. This statistical analysis of the before and after results is the second part of this paper.

The variability at PKO meant that the experimental methodology had to minimise the noise from the plant/ore. A test program was designed that would reduce this large inherent plant/ore variability. This test methodology is labour intensive but had proven successful elsewhere in detecting small differences relative to large variability (14). It was incorporated into the test program at PKO.

PKO Cu minerals vary from day to day, depending on the part of the pit where the ore is being mined, but they are predominantly sulphide minerals, primarily chalcopyrite, though the cyanide soluble Cu can vary from 10%-40%.

The experimental design was based on two premises. Firstly, that the effect of magnetic aggregation is on the finest <12 µm paramagnetic Cu mineral fraction, therefore, any testwork must focus on measuring a difference in recovery in this fraction. This removes the noise from the coarser particles. Cyclosizing was an important component of the process measurement. Secondly, where plant/ore variability is large, then plant assays and plant recoveries will also be variable. However, there is less variability in the Cu distribution in the size fractions. If plant operation is poor, cleaner tail assay may vary from 0.14% Cu to 0.28% Cu (at PKO); therefore, looking for a 0.01-0.02% change in Cu assay is difficult above the noise. However, the variability in Cu size distribution is much lower, because different ore is different across all the size fractions. For example at PKO, over the test period, the highest cleaner tail Cu assay for OFF <12µm faction was 250% of the lowest Cu assay; but the highest <12 µm Cu distribution was only 140% more of the lowest <12 µm Cu distribution. When Cu in tail is high, all size fractions will be affected, therefore, the distribution remains largely unchanged by this change. But, if magnetic aggregation is increasing fines recovery then a consistent reduction in the distribution of Cu in the finest fractions would be measured; independent of the absolute Cu assays.

The difficulty with this experimental methodology is practical. There is the added workload of sizing samples and there is the added opportunity for contamination when sizing many samples.

PKO limited the impact of these two difficulties. Sample numbers were reduced by making a weekly composite of all ON or OFF shifts for the week and then sizing and assaying these composites. Contamination was reduced by diligent supervision of the compositing, sizing and assaying of the samples.

Magnetic conditioning was installed in Cleaner 1A. A randomised, ON-OFF program was instituted for each 12 hour shift. For ON shifts the magnets were automatically lowered into the slurry and cycled in and out of the slurry (for cleaning). This operates automatically with a pneumatic control system. For OFF shifts the pneumatic system automatically lifts the magnets out of the slurry for the entire shift.

Automatic samplers, sample the cleaner 1A tails and cleaner 1B tails. The samples were collected and at the end of the week, an ON shift weekly composite and an OFF shift weekly composite was cyclosized. The fractions were assayed for Cu and cyanide (CN) soluble Cu. This week's data was an ON and OFF pair.

Part 2 Before and After Magnetic Conditioning Comparison

Because ore feed is overwhelmingly the major variable at PKO an ON-OFF paired t test is the recommended method for comparing two operating conditions (18). ON-OFF paired t tests effectively reduce ore variability as a biased variable, though it still remains as a random variable. However, statistically comparing before and after a plant change introduces the possibility of a trend bias favouring either condition, therefore, the results must be analysed with some caution; sympathetic to the possibility of bias. Optimally, the comparison should be immediately before the change to immediately after the change, thereby limiting the impact of a bias due to a systemic change in the ore. Also, other operational changes should not be made in conjunction with the change being measured.

In November 2016 after the good results achieved in the paired ON and OFF test the magnetic conditioning was installed in Cleaner 1B as well as Cleaner 1A. Automatic cleaner tails samples were composited over a week, cyclosized and assayed for Cu and CN sol Cu.

RESULTS AND DISCUSSION

Part 1 ON-OFF Statistical Test

There are twenty weeks of cleaner tails sizing and assays, each an ON and OFF data pair. This data was analysed using a paired t test and the statistical comparison summarised in Table 1.

Table 1. Statistical Comparison of ON Cleaner 1A and OFF Cleaner 1A

% <12 µm Distribution	Cu	CNsolCu	Mass
Magnetic Conditioning ON	39.1	53.7	51.1
Magnetic Conditioning OFF	42.2	56.5	52.3
Difference	3.1	2.8	1.2
Level of Confidence	97%	92%	low

The results demonstrate that magnetic conditioning reduced the Cu distribution in the <12µm fraction by about 7.5% for the total Cu and about 5% for the CN sol Cu. This is consistent with results at other sites and consistent with magnetic aggregation selectively increasing fine paramagnetic Cu sulphide recovery. The difference was detected to high certainty despite circuit variability. There was no reduction in other metals distribution in the <12µm fraction to high levels of certainty.

Another comparison can be made between the two cleaner lines 1A and 1B, both receive identical ore feed (the Jameson tail is split to the two cleaner lines) but their performance does vary slightly.

Table 2. Statistical Comparison of ON Cleaner 1A and OFF Cleaner 1B

% <12µm Distribution	%Cu	%Mass
Magnetic Conditioning ON Cleaner 1A	39.1	51.1
Magnetic Conditioning OFF Cleaner 1B	42.4	51.7
Difference	3.3	0.6
Level of Confidence	99%	low

Interestingly, these results show that the magnitude of the difference is similar between the magnetic conditioning ON in cleaner 1A and the magnetic conditioning OFF in cleaner 1A or 1B. But the level of confidence is higher when comparing cleaner 1A with cleaner 1B because comparing 1A and 1B compares results for identical shifts, therefore, ore feed was practically identical for both the ON and OFF shifts – variability is reduced.

The experimental methodology employed is validated because the <12 µm %Cu tail assay for each set of data; Cleaner 1A ON, Cleaner 1A OFF and Cleaner 1B OFF were not different to a high level of confidence. Clearly, the <12µm Cu distribution experimental methodology did detect a difference to a very high level of confidence, despite the variability.

Part 2 Before and After Comparison

From November 2016 when the magnetic conditioning was installed in both Cleaner 1A and 1B and operated continuously in both circuits the sizing and assay of the cleaner tails continued.

The comparison was of the 15 weeks before the change and the 15 weeks after the change. This was a good data set; not too large so as to be too distant from the change-over, but large enough to give a substantial data set, that can be statistically analysed with a two sample t test. The results to high confidence for the <12µm fraction are given in the Table 3.

Table 3. Statistical Comparison of After and Before Magnetic Conditioning Installation

	%Cu Cl Tail	%Cu Dist Cl Tail	%Cu Rec Cleaner	%Cu 3rd Cl Conc
After (Mag Cond Always ON)	0.16	33.3	94.1	27.4
Before (Mag Cond Always OFF)	0.20	39.6	92.3	25.9
Difference	0.04	6.3	1.8	1.5
Level of Confidence	99%	99.9%	99%	96%

The data shows that by a variety of measurements magnetic conditioning is reducing the <12 µm Cu losses to the cleaner tail, and concurrently increasing the <12 µm Cu concentrate grade. This result is a definite improvement in the <12 µm Cu grade – recovery response with increases in Cu recovery and grade. The technology is selective so that the paramagnetic Cu sulphides increase the grade of the <12 µm fraction, even at the higher Cu recovery.

There was no change to high confidence for other circuit parameters. This confirms that the before and after data was unaffected by changes in ore or plant performance.

The before and after testwork is consistent with, and confirms the statistical ON-OFF testwork and validates the methodology used. However, the results while validating the ON-OFF testwork are markedly better in magnitude than the Part 1 testwork. In Part 1 the reduction in <12 µm Cu distribution in tail was about 7.5%, whereas this testwork is showing the decrease to be closer to 20%; threefold larger. Whereas, in Part 1 while there was no difference in <12µm Cu assay in tail to high confidence, Part 2 shows a decrease of about 20% to high confidence with magnetic conditioning. Therefore, while the results are confirmatory, they are very different in magnitude. Moreover, partly because of this greater magnitude the confidence levels are higher than in Part 1.

There are two possible explanations for the magnitude difference between Part 2 and Part 1. Firstly, it could be that there was large change in the ore/plant coincident with the magnetic conditioning installation. Secondly, there could be an equilibrium effect with magnetic conditioning that wasn't seen in the Part 1 shift ON/OFF test because a shift is not sufficient to see the full effect of magnetic conditioning through all the recirculating streams in the cleaner.

While it is unlikely there was large change in the ore/plant coincident with the magnetic conditioning installation, this coincidence is possible. However, no change was noticed in the plant in other areas. Moreover, there was no step change to a high level of confidence in other <12µm data in the cleaner circuit. The before and after <12µm fraction data for: %Cu in rougher concentrate and size distribution; %Cu in the Jameson tail and size distribution; the <12µm %Cu recovery in the Jameson cell are not statistically different. Therefore, there is no detectable step change in these measures. The only step change is the changes expected with magnetic conditioning.

The possibility that a 12 hour shift is not sufficient to see the full extent of the change with magnetic conditioning is supported by testwork elsewhere. The testwork at Red Dog showed that after an equilibrium period magnetic conditioning results improved (10), and the results at Kevitsa showed a similar improvement (11). This is the likely explanation at PKO, where the magnetic conditioning was randomly switched ON and OFF on a short 12 hourly basis. It is evident from other sites (Red Dog and Kevitsa) that the effect of magnetic conditioning is not fully measured in the plant until after a 24 hour equilibration period. Of course this is circuit specific, and maybe shorter or longer depending on the circuit, nevertheless, this seems a much more likely explanation for the large difference between the results in Part 1 and Part 2. It is not that the impact of magnetic conditioning is not measureable without an equilibration period, but that the full magnitude of the impact is only measured after the circuit has equilibrated to the new condition.

PKO produces a Cu concentrate with payable Au. However, the specific objective of the test program was to look for changes in Cu losses in the fine fraction, not Au losses because Cu is PKO's primary revenue stream. While magnetic conditioning has positively impacted Au recovery at other sites (12) it was not part of the experimental methodology at PKO.

The ON-OFF test showed an increase in Au grade in final concentrate for the days that magnetic conditioning was operating to high confidence. This does indicate a higher recovery with magnetic conditioning, but because the Au in tails was not lower and the economics of magnetic conditioning was not dependent on the Au recovery this data is not presented.

Financial Outcomes of Testwork

Using the method of Zoetbrood (14), the value benefit with magnetic conditioning from the ON-OFF test was around 300t/yr of extra Cu. Depending on concentrate contracts and metal prices the value of this benefit is more than USD1.5million per year, a multiple of the cost of magnetic conditioning. This multiple times financial benefit is to 97%-99% certainty

However, with the results from Part 2 of the testwork showing a 3 times larger metallurgical benefit with the magnetic conditioning the financial benefit is also 3 times larger. The financial benefit is about 900t/yr of extra Cu or more than USD4.5million per year of extra Cu to greater than 99% certainty. This return on investment is very much more than 10 times the cost to greater than 99% certainty.

CONCLUSION

As part of PKO's ongoing commitment to improving plant performance, magnetic conditioning was tested in the plant. Extensive plant evaluation has shown that magnetic conditioning has improved <12µm Cu recovery at PKO. Moreover, a methodology developed by Zoetbrood (14) has been used that overcomes large plant variability to give a result to very high levels of statistical confidence. Statistical comparison of plant results before and after the introduction of magnetic conditioning has confirmed the paired ON-OFF testwork, But it shows that the real plant change with magnetic conditioning is about 3 times the benefit measured in the paired ON-OFF test. Most likely this is because equilibrium had not occurred in the paired ON-OFF test. The results are to 99% statistical confidence and have an economic benefit of about 10 times the cost.

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