# Improving Fine Copper and Gold Flotation Recovery — A Plant Evaluation

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## ABSTRACT

A statistical 'randomised block design' full plant trial of magnetic conditioning of flotation feed was undertaken at Rio Tinto's Northparkes Mine in New South Wales. Magnetic conditioning of flotation feed has been shown to improve the flotation of <38 μm paramagnetic minerals consistent with selectively aggregating these paramagnetic minerals. The process was evaluated using shift composite samples that were analysed for copper and gold. Because the process targets <38 μm minerals, all samples were sized and the size by size recoveries were calculated for each sample. The size by size analysis targeted the effect on fine mineral, reduced the plant noise and shortened the test period required to get statistically significant results. An increase of gold and copper recovery was found in the <20 μm fraction to a high level of statistical significance. For the >20 <38 μm size range the copper recovery increased to a high level of significance, whereas the increase in gold recovery in this fraction was to a lower statistical significance. There was no statistical improvement in the >38 μm fraction for either metal. Approximately half the copper and gold losses at Northparkes are in the <20 μm size fraction. While the sulfide copper minerals chalcopyrite and bornite are known to be paramagnetic; gold is not paramagnetic. Gold's response to magnetic conditioning, however, is consistent with a number of literature references where, depending on the gold's mineralogical disposition, gold has been shown to respond to magnetic treatment.

## INTRODUCTION

The operational efficiency of all mineral separation processes is within certain limits. These limits can be reduced and the efficiency increased by the introduction of new technology that enhances the mineral separation process. These enhancements may be expanding the parameters over which the process can be applied, reducing the cost of the process or by improving the efficiency of separation within existing parameters. It is not enough for the operation of a commercial plant that the efficiency of the mineral separation technology can be enhanced in a laboratory, or only be shown to do so in a laboratory. For a new technology to be practical the efficiency must be enhanced in a way that is applicable to commercial mineral processing operations. Applicability to commercial mineral processing operations means that the technology can be practically applied to existing operations, that the improvement can be clearly demonstrated in the operation and that it is economically and operationally beneficial.

Furthermore, a mill operator must be able to evaluate a new technology in a commercial plant with all the normal background variability associated with hour to hour operations of the plant but not related to the test (commonly termed noise), that occurs in such a plant and be able to measure or see that the benefit is real. Given the efficiency of modern mineral separation technologies it is unrealistic to expect that a new technology is going to give a benefit so large that it is immediately obvious. Rather the benefit is going to be relatively small and at the margins of the operation and only apparent to the operator after a period of statistical testing. Nevertheless, such a benefit, while only measured in single digit percentage points will be of immense economic benefit and valued at many millions of dollars of revenue, easily justifying the effort of the evaluation.

### Recovering fine sulfide minerals by flotation

Froth flotation of minerals is a technology that has been used commercially for around 100 years. Over the 100 years, significant resources have been expended on new technologies to improve its efficiency. Among these new technologies have been chemically based technologies, mechanically based technologies and technologies devoted to the operational control of the process. These new technologies have improved the efficiency of froth flotation significantly.

However, one of the major limitations in froth flotation remains the efficient, selective recovery of minerals less than 10 μm in size. (Trahar, 1981; Trahar and Warren, 1976). These <10 μm valuable minerals continue to present a challenge to operators of froth flotation plants. Improving the efficiency of separation of these <10 μm particles offer the operator of a froth flotation plant the opportunity to enhance the economic viability of their operation. Moreover, all froth flotation plants, even those that grind to a coarse size range inevitably find that a large component of their losses are these <10 μm particles.

It is generally accepted that the poor recovery and efficiency of separation of <10 μm sulfide particles is only due to their size. It is not chemical but purely physical, and due to their poor collision efficiency with the air bubble (Trahar, 1981).

Many and various strategies and technologies have been investigated over the years to improve the recovery of fine sulfide mineral. These efforts have had some success. Fuerstenau, Chander and Abouzeid (1979) outline in detail some of the different strategies and technologies that have been investigated to improve the recovery of fine mineral. The strategies and technologies that have been investigated have been both chemical and mechanical. One method that has been investigated has been to aggregate the fine mineral. Sivomohan (1990) details some of the aggregation processes investigated, which have included mechanical methods such as high intensity conditioning (shear flocculation) and chemical aggregation methods such as those using flocculants or salts.

Some of the important problems that fine particle aggregation methods have had to overcome to be utilised successfully in industrial plants is; their lack of selectivity, their large capital and operating costs and the fragility of the aggregates in industrial flotation plants. Failure of an aggregation method to overcome any one of these barriers results in the method being unsuitable in an industrial plant.

Of the aggregation methods in the literature, none appear to have received widespread acceptance in commercial flotation operations.

### Magnetic aggregation of fine paramagnetic minerals

That magnetic particles will aggregate when magnetised has been known for decades. However, it was only with the development of very high strength magnetic fields that the

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investigation of aggregating paramagnetic particles occurred. Svoboda (1987) gives a very good outline of the factors effecting magnetic aggregation of paramagnetic particles. From a practical perspective most of the literature outlines laboratory experiments or theoretical modelling of the process, and do not generally apply the process to the valuable paramagnetic sulfide particles that are recovered by flotation. Nor does the extensive literature apply the process to flotation. However, the theoretical and laboratory basis is equally applicable to sulfide as well as non-sulfide minerals.

Engelhardt, Ellis and Lumsden (2005) have clearly demonstrated that magnetic aggregation of fine paramagnetic particles can be used to increase the flotation recovery of the fine paramagnetic minerals chalcopyrite and sphalerite. Their paper summarises the literature that outlines the theoretical basis of aggregation of fine paramagnetic particles.

## Gold mineralogy

Gold, particularly when found in base metals ores is often recovered by froth flotation. Gold mineralogy, whether in base metal ores or other ores, can be complex. Though mostly occurring as gold metal, rather than a gold mineral, it can occur as free native gold or be associated with different minerals in the ore, depending on the nature of the ore formation. The difficulty in being precise about gold mineralogy is that in most flotation ore the gold is in such low concentrations that seeing the gold is difficult, therefore understanding much about its occurrence and associated mineralogy is also difficult (Henley, 1975).

Table 1 shows that gold is not paramagnetic but it is diamagnetic. This means that with magnetic fields of industrial strength gold is not magnetised. However, gold in its distribution within the ore may be associated with paramagnetic minerals such as chalcopyrite or marmatite. The literature contains a number of studies where magnetic separation methods have been used to concentrate and recover gold (Corrans and Levin, 1979; Corrans, 1980; Corrans and Dunne, 1985; Ciesla, 2003). Gold that can be recovered by magnetic separation is gold that occurs in minerals with a strong magnetic susceptibility, because the concentration of paramagnetic minerals is only moderately successful by magnetic separation.

**TABLE 1**

*Magnetic susceptibility of minerals and gold.*

| Mineral | Reported magnetic susceptibility (Svoboda, 1987) ($M^3kg^{-1} \times 10^{-9}$) |
|---|---|
| Chalcopyrite | 1595.9 |
| Bornite | 100.5 |
| Marmatite | 38 - 5900 |
| Cassiterite | 2136.3 |
| Pyrite | 1 - 5 |
| Quartz | -5.7 |
| Gold | -0.15 |

Laboratory scale test work undertaken by Corrans and Levin (1979), with wet high intensity magnetic separation (WHIMS) on a range of samples from ore to leach or flotation tailings gave gold recoveries in the magnetic fraction of up to 95 per cent. Other researchers (Corrans, 1980; Watson, Rassi and Bahaj, 1983; Corrans *et al*, 1984; Corrans and Dunne, 1985; Conway and Dunne, 1986; Svoboda, Corrans and Spitze, 1986; Svoboda, Lazer and Te Riele, 1987) have published laboratory and plant test work on the recovery of gold from Witwatersrand ore and residue by WHIMS. Ciesla (2003) recovered more than 70 per cent of the gold from copper flotation tailings by high gradient magnetic separation (HGMS).

The mineralogy of the gold that resulted in it having a high magnetic susceptibility is not clearly demonstrated. Low levels of gold make mineralogical analysis problematic. However, explanations by the above authors range from: gold in sulfide minerals, gold in silicates, gold in oxide minerals, gold containing iron or gold with iron or iron oxide coatings.

Martinez (1988a, 1988b) applies a coating of colloidal iron or iron hydroxide to ores and tailings to magnetise the gold particles so that they can be recovered by magnetic separation.

Gold may also be closely associated with sulfide minerals such as chalcopyrite, galena, bornite, pyrite and arsenopyrite (Henley, 1975). Some of these minerals are paramagnetic, so that gold may be concentrated magnetically if the associated sulfide can be concentrated magnetically.

Bheemalingeswara (1995) has shown that the coating of gold particles with iron oxide/iron hydroxide gave the particles sufficient magnetic susceptibility to be concentrated in the laboratory by magnetic separation.

In summary, gold's disposition in the ore as well as in the mineral flotation slurry will determine whether the gold is amenable to magnetic methods. Other researchers have shown that gold can be associated with paramagnetic minerals, or with magnetic minerals, or has iron impurities within the gold matrix, or is coated with a magnetisable iron coating. Gold in any of these forms has been shown to respond to magnetic methods. In the flotation process where paramagnetic minerals such as chalcopyrite are being recovered then increasing the recovery of fine chalcopyrite would be expected to increase the recovery of the fine gold associated with the chalcopyrite. As well, in the flotation slurry there is fine metallic iron and iron hydroxides, generated from the grinding process and the normal alkaline flotation conditions, so that it is possible that the free gold or even gold on the surface of a silicate particle may absorb iron or iron hydroxides and so be able to be magnetised and aggregated.

The gold in the ore at Northparkes mine is mostly found disseminated as fine particles, most particles are less then 5 μm. The particles are generally associated with the copper bearing sulfide minerals; however, there is a significant percentage found along the grain boundaries of the silicate host rock.

## Randomised block design trials

Napier Munn (1995) outlines in detail some paired methods for testing process variables with specific reference to mineral processing operations. The paper gives an excellent outline of randomised block design trials. As Napier-Munn identifies, the main advantage of randomised block design methodology is that:

> *it allows the significance of the main effects and their interactions to be rigorously tested (are they real or aren't they?) whilst eliminating and indeed separately testing for, the effect of the interfering factor (here time).*

Randomised block design uses the analysis of variance (ANOVA) statistical procedure to evaluate the data.

Napier-Munn (1995) identifies that the key to evaluation in the minerals processing industry is to determine whether a real difference is occurring above the daily variations of the noise of the plant. This is the critical part of plant evaluation. The process change may be effective in the laboratory and even effective in the plant but being able to 'see' its effectiveness and determine that the effect is real is the crucial technique.

One way to improve the ability to 'see' a change in the plant is to reduce the background noise. Since magnetic aggregation only affects the recovery of fine mineral, with great insight the Northparkes mine site personnel further modified the normal design of the experiment so that the flotation performance of the fine mineral could be determined separately from the coarse mineral. All samples were sized at 20 µm and 38 µm. As the results show this significantly reduced the variance and allowed the difference to be 'seen' much more readily. Particularly in the case of determining gold recovery this was effective. Coarse gold in a sample is notoriously difficult to accurately measure and so removing this coarse gold noise from the testing was vital. This sizing step was a significant change in methodology to normal trials and may have more widespread implications.

### Northparkes mine and operation

The Northparkes copper-gold mine is located in the central west of New South Wales and has been operating since 1993. The operation is a joint venture between Rio Tinto and the Sumitomo Group.

A diagram of the Northparkes Module 2 flow sheet is given in Figure 1. The processing plant comprises two parallel modules, Module 1 with a design capacity of 245 t/h and Module 2 with a design capacity of 423 t/h. Ore is crushed and then ground in a SAG mill and two stages of ball milling to a flotation feed size (P80) of 95 - 110 µm. Flash flotation is used in the grinding circuit to recover the free floating course material; the grinding is followed by conventional flotation that consists of rougher scavenger banks with NaHS, frother, xanthate and thiono-carbamate as chemical additives. The rougher concentrate is then cleaned by Jameson cells to produce the final copper gold concentrate.

Concentrate is thickened and filtered and sold by contract and on the spot market for smelting. Tailings after thickening report to the tailings dam.

Copper mineralogy is a mixture of chalcopyrite and bornite. There is little associated pyrite.

### Testing methodology

Testing was carried out on Module 2. The flotation module has two large existing conditioning tanks that were used for NaSH conditioning when high oxide ore was treated. The ProFlote® magnetic conditioning devices were installed in the second of these conditioners where the slurry residence time is 2.5 minutes. The ProFlote® conditioning devices consist of high strength high gradient rare earth permanent magnets arrayed within a stainless steel assembly. The strong magnetic field of about 5000 gauss contacts the slurry. At frequent and regular intervals the magnets are automatically removed from the slurry to allow for the removal of ferromagnetic material that may blind the magnets.

A randomised block design program was used. The first day after turning the magnetic conditioners 'on' or 'off' was an equilibration day and the second day was a test day. The nature of randomised block design testing is that paired samples are taken. Randomising and pairing is established at the beginning of the testing and locked in for the trial period. If during one of the pairs there is a major plant shutdown or disturbance for a prolonged period of time, or sampling or laboratory issues occur then both data points in the pair are discarded. Once the testing was standardised and underway and a few teething problems solved about 70 per cent of the data was considered useful. Most of the discarded data related to an automatic sampler problem, or one of the ball mills being down for maintenance. The more intensive sample preparation in the laboratory did not present a problem after the teething period.

The plant automatic samplers sample the final concentrate, final tail, plant feed and flash float tail (flotation feed). This presented a problem in the testing because the final concentrate includes the flash concentrate. For the test work either the final concentrate could be used or the concentrate excluding the flash concentrate sampled manually. Because the flash concentrate has a very low quantity of fines, and because the manual sample is inherently inferior to an automatic sample, it was decided to use the automatic final concentrate sample. Automatic samplers took normal shift composite samples and these samples were assayed as well as subsamples being split for size analysis. Samples were sized at 20 µm and 38 µm with the +38 µm sizes being combined.

Plant operation was monitored so that on days where a mill was shut down or some other major change occurred samples were discarded. Note that the block design makes it highly unlikely for the results to be biased by the flash float concentrate being included in the concentrate sample. Changes in flash float performance will only increase the noise in the data.

## RESULTS AND DISCUSSION

The results from the randomised block testing are summarised in Table 2 for copper and Table 3 for gold.

There is no statistical difference between the feed grades, concentrate grade or copper and gold distribution in the different size fractions.

The analysis of variance of the recovery for the different fractions for copper and gold are given in Table 4 for copper and Table 5 for gold.

### Copper results

The copper recovery increase in the <20 µm fraction and the 20 - 38 µm fraction has been shown by ANOVA analysis to be, in Napier-Munn's (1995) terms, real. The best estimate of the increase in copper recovery is the difference in the means, which is 2.08 per cent for the <20 µm fraction and 0.98 per cent for the 20 - 38 µm fraction. The results, increased recovery in the finer fractions and no increase in recovery in the coarser fractions, are consistent with a mechanism of magnetic aggregation of fine paramagnetic minerals improving their flotation. The results are consistent with those of Engelhardt, Ellis and Lumsden (2005).

Although the grind size is not particularly fine at Northparkes it is interesting to note that about 70 per cent of the copper is less than 38 µm. It is also worth noting that sizing the sample allowed for a significant reduction in the noise with the standard deviation of the paired differences being much lower in the <38 µm fractions compared to the >38 µm fractions. This meant that the statistical significance in the <38 µm fractions was much higher than for the total sample, shortening the trial and giving greater confidence in the results.

### Gold results

The gold recovery increase in <20 µm fraction has been shown by ANOVA analysis to be 'real' with the best estimate of the increase being the difference in the means, which is 3.51 per cent. Again, the increase in the gold recovery was for the finest fraction with no real increase in the coarser fractions. This is consistent with an aggregation mechanism. Of particular note is the substantial increase in the standard deviation for the coarser size fractions. Despite as large or larger differences in the means the results cannot be said to be real because the standard deviations for the courser size fractions are so large. Given that about 50 per cent of the gold in the feed is in the >20 µm fraction, the very large standard deviations in gold recovery for these fractions means that testing to demonstrate a real difference in recovery over the whole sample (without sizing) would have required a very long trial.

There is not sufficient data, nor sufficient gold in this very low-grade gold ore to determine on which gold the ProFlote is impacting. Whether magnetic aggregation is impacting on the fine gold associated with copper sulfide minerals; bornite and chalcopyrite; or with fine free gold that has a magnetite or iron-hydroxide coating or whether it is some other paramagnetic or ferromagnetic mineral it is impossible to say.

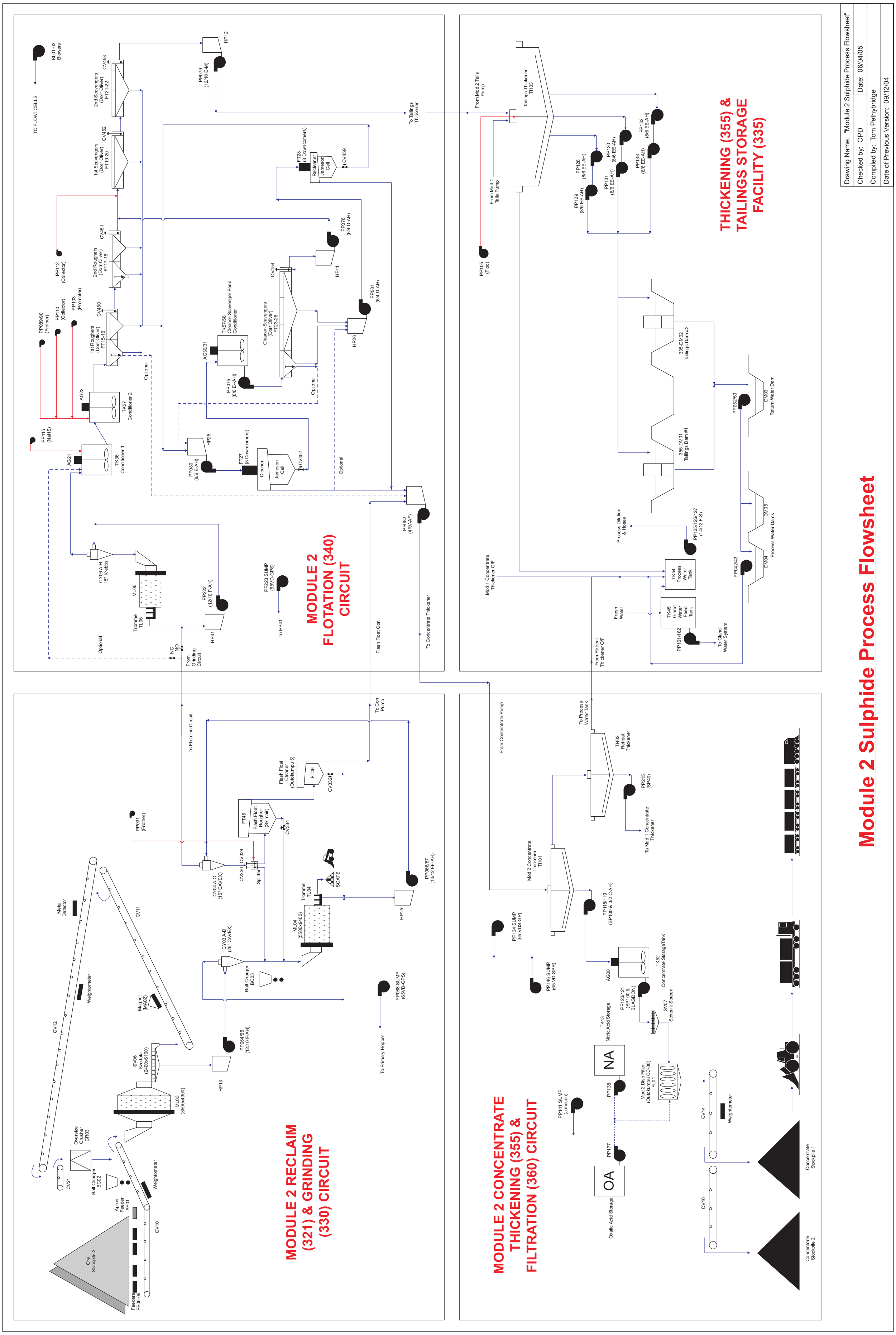


FIG 1 - Northparkes module 2 flow sheet.

**TABLE 2**

*Mean copper results for 'on' and 'off' days.*

| Fraction | Feed (%Cu) | Conc grade (%Cu) | Tail (%Cu) | Recovery (%) | Distribution (% of Cu in feed in fraction) |
|---|---|---|---|---|---|
| <20 µm ON | 1.098 | 43.15 | 0.119 | 89.34 | 52.3 |
| <20 µm OFF | 1.075 | 43.27 | 0.139 | 87.26 | 53.7 |
| >20 <38 µm ON | 1.199 | 45.41 | 0.033 | 97.28 | 18.7 |
| >20 <38 µm OFF | 1.134 | 45.36 | 0.043 | 96.30 | 18.1 |
| >38 µm ON | 0.395 | 28.67 | 0.107 | 73.06 | 29.0 |
| >38 µm OFF | 0.392 | 29.00 | 0.111 | 71.86 | 28.2 |

**TABLE 3**

*Mean gold results for 'on' and 'off' days.*

| Fraction | Feed (ppm Au) | Conc grade (ppm Au) | Tail (ppm Au) | Recovery (%) | Distribution (% of Au in feed in fraction) |
|---|---|---|---|---|---|
| <20 µm ON | 0.48 | 17.09 | 0.07 | 86.15 | 51.1 |
| <20 µm OFF | 0.47 | 17.02 | 0.08 | 82.86 | 53.2 |
| >20 <38 µm ON | 0.32 | 9.99 | 0.11 | 66.66 | 11.8 |
| >20 <38 µm OFF | 0.30 | 9.80 | 0.11 | 62.54 | 11.4 |
| >38 µm ON | 0.21 | 5.79 | 0.15 | 29.47 | 37.1 |
| >38 µm OFF | 0.22 | 6.16 | 0.16 | 26.33 | 35.4 |

**TABLE 4**

*ANOVA analysis of copper results.*

| Fraction | % Difference | Std dev | Degrees of freedom | 'F' | Significance |
|---|---|---|---|---|---|
| <20 µm | 2.08 | 3.0 | 13.1 | 6.78 | >97,5 |
| >20 <38 µm | 0.98 | 1.1 | 13.1 | 11.84 | >99 |
| >38 µm | 1.20 | 4.6 | 13.1 | 0.94 | N.S |

**TABLE 5**

*ANOVA analysis of gold results.*

| Fraction | % Difference | Std dev | Degrees of freedom | 'F' | Significance |
|---|---|---|---|---|---|
| <20 µm | 3.51 | 3.8 | 12.1 | 11.37 | >99 |
| >20 <38 µm | 3.43 | 9.0 | 12.1 | 1.88 | N.S |
| >38 µm | 3.17 | 18.9 | 12.1 | 1.49 | N.S |

Engelhardt, Ellis and Lumsden (2005) showed that magnetic aggregation could increase the recovery of silver, a metal that like gold often occurs in elemental form in ores and is also diamagnetic. These gold results are then consistent with the results presented by Engelhardt, Ellis and Lumsden (2005).

### Economic impact

The economic impact of these improvements in recovery to Northparkes mine are substantial. This technology is now part of the Northparkes flow sheet, and testing on Module 1 will commence in 2007.

## CONCLUSION

Magnetic aggregation has been shown to improve the efficiency of separation of flotation by improving the recovery in the fine fractions. Both copper and gold recovery in the fine fractions has increased. These increases are real and beneficial. The results are consistent with a magnetic aggregation mechanism.

Because magnetic aggregation targets the fine fractions these fractions were separately assayed and the improvement was shown to occur in these fractions alone. Targeting the fine fractions in carrying out the trial reduced the plant noise and allowed the improvement to be 'seen' more quickly.

The randomised block design method has also been shown to be effective in 'seeing' these improvements.

Perhaps one of the major innovations of this work is the use of sized samples to reduce the plant noise. While this has been specifically applied to a process that targets fine mineral, the methodology may also be applicable to other processes that don't necessarily target fine mineral. For instance, in testing a process change that the laboratory has shown to improve the process across all sizes it might be beneficial in the plant to measure the effect on the total sample as well as specifically the fine fraction.

Particularly in the separation of gold, measuring the effect on the fine fraction where the variance is much smaller might be an indicator of what is happening across all sizes, especially if the laboratory demonstrates this is an appropriate conclusion. Or it may be sufficient to the plant that the process improves the fine gold recovery alone. Whichever, looking at changes in size fraction recovery could be a preferred or additional method of testing that allows the operator to see small 'real' differences more readily, than with a non-sizing testing method.

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