

Magnetic Conditioning of Pentlandite Flotation-Plant Evaluation

D. Zoetbrood, P. Vass, and B. Lumsden.

ABSTRACT

Magnetic conditioning of flotation feed has been shown to increase the flotation recovery of fine paramagnetic minerals. Previously published work has been undertaken on the well-known paramagnetic sulphide minerals of copper (chalcopyrite and bornite) and zinc (sphalerite containing iron). The paramagnetism of pentlandite is not widely published, but the plant testwork presented here shows that magnetic conditioning of pentlandite flotation feed gave a statistically significant increase of up to 0.85% in nickel recovery. Magnetic conditioning was selective for nickel giving a better nickel grade - recovery curve with an increase in nickel recovery at the same concentrate grade. One interesting aspect of the work was that this increase in fine nickel recovery was selective for nickel, despite the ore containing significant quantities of other paramagnetic minerals, primarily pyrrhotite. The increase in nickel recovery in the rougher circuit was similar in a massive sulphide ore and in a disseminated ore. Another interesting aspect of some of the testwork was that only the tail could be sampled automatically and so an ON-OFF test was undertaken where the effectiveness of the process was determined by analysing the proportion of <38µm nickel in the tail.

Key Words

Agglomeration, froth flotation, fine particle processing, sulphide ores

INTRODUCTION

Magnetic conditioning of flotation feed has been shown to increase plant flotation recovery of fine paramagnetic sulphide minerals (Engelhardt *et al.*, 2005; Rivett *et al.*, 2007; Holloway *et al.*, 2008; Bott and Lumsden, 2009). Magnetic treatment of fine paramagnetic minerals and fine hydrophobic paramagnetic minerals has been shown to cause these minerals to aggregate. This technology suits flotation plants recovering fine paramagnetic minerals and losing <38µm mineral to the tails. Of course the plant must lend itself to statistical testing to allow the difference in flotation recovery to be measured. Most, if not all sulphide flotation plants have a high proportion of their flotation losses in the <20µm fraction.

The other suitability requirement, that the floated minerals be paramagnetic is a more complex issue. The literature of the magnetic susceptibility of naturally occurring paramagnetic minerals is not extensive, and is not necessarily consistent (Andres, 1976; Svoboda, 1987; Hunt *et al.*, 1995). Moreover, the literature is clear that for naturally formed minerals (as opposed to laboratory synthesized minerals) the magnetic susceptibility varies significantly. Svoboda (1987) gives a range for the

magnetic susceptibility of naturally occurring sphalerite of $3.8 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ to $5.9 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$, a difference of two orders of magnitude. Svoboda (1987) and Andres (1976) both list the magnetic susceptibility of chalcopyrite as being greater than that of bornite, whereas Gaudin and Rush-Spedden (1943) found that bornite has a greater magnetic susceptibility than chalcopyrite. Holloway *et al.* (2008), contrary to the literature, found that galena at BHP-Billiton's Cannington mine was strongly paramagnetic, probably due to iron inclusion in the galena matrix.

Surprisingly, the magnetic susceptibility of the naturally occurring nickel sulphide, pentlandite is not mentioned in the lists provided by Andres (1976), Svoboda (1987) or Hunt *et al.* (1995). Andres (1976) notes the nickel sulphide millerite is diamagnetic, but doesn't refer to the more important nickel sulphides pentlandite and violarite. Svoboda (1987), Hunt *et al.* (1995) and Gaudin and Rush Spedden (1943) do not discuss the nickel sulphides at all. Rubinstein and Barsky (2002) give the magnetic susceptibility of pentlandite as comparable to chalcopyrite.

A further level of complexity also occurs for pentlandite $(\text{NiFe})_9\text{S}$ because the actual nickel: iron ratio of pentlandite can vary within an orebody and from orebody to orebody. The different ratio of Fe: Zn in sphalerite has been shown to significantly affect its magnetic susceptibility (Svoboda, 1987) and so it could be expected that the magnetic susceptibility of pentlandite would also vary significantly depending on the Ni: Fe ratio.

Yet a further complication to measuring the magnetic susceptibility of pentlandite is that it usually occurs with other iron sulphides, particularly pyrrhotite, which itself has a well-known variability in its magnetic susceptibility. Therefore, it is complex to measure accurately the magnetic susceptibility of pure naturally occurring pentlandite in an orebody.

Fine sulphide mineral recovery by flotation

The efficiency of fine sulphide mineral flotation decreases as particle size decreases below $20 \mu\text{m}$. Jameson *et al.* (2007) have published an excellent review of the current research investigating the poor efficiency of fine mineral flotation separation. Duan *et al.* (2003) investigated the recovery of fine chalcopyrite in a stirred vessel. They modelled the collection efficiency (E_K) as a combination of the attachment efficiency (E_A), the collision efficiency (E_C) and the particle-bubble stability efficiency (E_S).

$$E_K = E_K \cdot E_A \cdot E_C \quad 1$$

The critical parameter for fine minerals is the collision efficiency, because E_A increases as particle size decreases and E_S is high for fine particles in a stirred vessel. Poor recovery of fine sulphide minerals is due to their poor collision efficiency with the bubble. Others, (Dobby and Finch, 1987; Jameson *et al.*, 2007; Ahmed and Jameson, 1985, 1989) have shown that fine particle recovery can be increased by: decreasing bubble size, increasing particle velocity, or increasing particle size. Both decreasing bubble size and increasing particle velocity decreases selectivity (Dobby and Finch, 1987; Ahmed and Jameson, 1985, 1989), indicating that increased fine particle selective flotation recovery can best be improved by increasing particle size through a selective aggregation process.

The recovery of pentlandite, like other sulphides is significantly reduced as particle size decreases (Ahmed and Jameson, 1989). Their paper shows that for pentlandite the drop in recovery occurs at around 20 μ m a much larger particle size than for galena and sphalerite whose recovery decreases at around 10 μ m. This suggests that pentlandite flotation is more sensitive to particle size than galena or sphalerite flotation.

The literature contains a large number of studies of methods to increase fine sulphide flotation mineral recovery; these include methods based on aggregation, reagents, and flotation equipment and flotation strategies. Fuerstenau *et al.* (1979) has reviewed many of the published methods. Most of these studies concentrate on the more commonly recovered sulphides of copper, zinc or lead, or non-sulphide minerals. The application of these mostly laboratory studies have not advanced to the widespread introduction of plant changes to specifically target fine sulphide mineral.

In Australia the method that has gained the most practical application is split flotation and it has been introduced to a number of nickel flotation operations, and the lead flotation plant at Cannington mine (Torrison and Smith, 2003). This is a change in flotation strategy rather than an improvement in flotation technology. Split flotation is based on floating the fine mineral usually the <20 μ m mineral separately to the coarse mineral and giving this finer mineral longer flotation residence time and increased reagent dosages.

Blackwell *et al.* (1992) investigated shear-flocculation in the laboratory as a method to improve the recovery of fine pentlandite. Shear-flocculation increased pentlandite flotation kinetics but overall pentlandite recovery did not increase.

Selective aggregation of fine sulphides, have also been investigated (Song *et al.*, 2000, 2001; Peng *et al.*, 2005) but with mixed results. Peng *et al.* (2005) found that there was no increase in the flotation recovery of chalcopyrite after floc-flotation compared with fresh chalcopyrite without floc-flotation, whereas Song *et al.* (2000, 2001) found a 10% increase in sphalerite recovery with floc-flotation.

Magnetic aggregation of fine minerals

Magnetic separation has been associated with pentlandite flotation. It has been common plant practise for pyrrhotite to be removed from either nickel flotation feed or from nickel concentrates by magnetic separation, with the pentlandite reporting to the non-magnetic fraction. Yalcin *et al.* (2000) has shown in the laboratory that pentlandite separation efficiency can be improved by combining flotation with magnetic separation of pyrrhotite from the flotation concentrate. But the magnetic aggregation of nickel sulphide minerals has not been reported.

The magnetic aggregation of fine paramagnetic minerals has been extensively studied in the laboratory and mathematical models have been derived (Svoboda, 1987; Lu *et al.*, 1988; Skvarla and Zelenak, 2003). Magnetic aggregation of hydrophobic paramagnetic particles can be expressed as a combination of the four particle-particle energies:

$$V_T = V_M + V_A + V_R + V_H \quad 2$$

Where,

V_A is the energy of attraction known as the London-Van der Waals energy

V_R is the energy of repulsion due to the electric double layer

V_M is the energy of attraction of magnetized minerals

V_H is the energy of association due to the hydrophobicity of minerals

Of importance for magnetised paramagnetic particles is the magnetic attraction that has been shown (Svoboda, 1987) to be given by the formula:

$$V_M = (8\pi\kappa_1\kappa_2b_1^3b_2^3B^2) / (9\mu_0\{h+b_1+b_2\}^3) \quad 3$$

Where,

μ_0 is the magnetic permeability of a vacuum

κ_1 and κ_2 are the volume magnetic susceptibilities of the particles

b_1 and b_2 is the radius of the particles

B is the magnetic induction

h is the distance between the surfaces of the particles

Therefore, V_M is dependent on κ , b and B .

V_M is proportional to κ the magnetic susceptibility of the mineral

V_M is proportional to b the radius of the mineral

V_M is proportional to B the magnetic induction

Pentlandite flotation operation

Plant testwork was carried out on a pentlandite flotation operation located in Western Australia. The flotation plant treated two ore types; firstly it treated a massive sulphide ore and then a disseminated ore. The magnetic conditioning was evaluated on the plant on both ores.

The ore treated had a high content of strongly magnetic material. This was about 22% in the rougher feed. The magnetic susceptibility of the nickel concentrate after the removal of the strongly magnetic material was $2200 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$. The magnetic susceptibility of this concentrate is comparable with the magnetic susceptibility of chalcopyrite (Svoboda, 1987), and so consistent with the work of Rubinstein and Barsky (2002).

Massive sulphide ore

The circuit configuration used for treatment of the massive sulphide ore consisted of a 2 stage crushing circuit producing a mill feed with an $F_{80}=8.5\text{mm}$ which reported to a fine ore bin prior to reclaim as mill feed. Reclaimed ore was fed to a single stage overflow ball mill operating in closed circuit with a cyclone cluster. Cyclone underflow material went through a flash flotation stage prior to reporting back to the ball mill for further grinding. Cyclone overflow reported to a conditioning tank prior to entering the main float circuit. Float circuit consisted of a rougher/scavenger stage with 2 stages of concentrate cleaning. Cleaning circuit tail combined with

rougher/scavenger tail to form the final tails stream. The magnetic conditioning unit was installed on the cyclone overflow line prior to the conditioning tank.

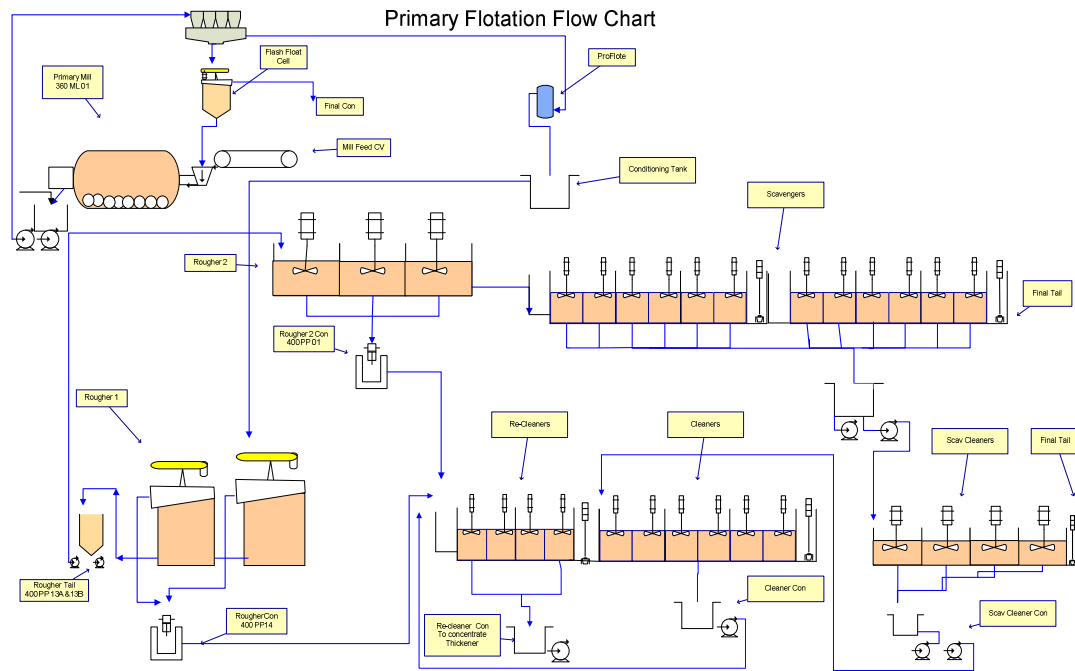


Fig. 1. Massive sulphide ore flowchart

Mineralogy of the massive sulphide ore consisted of pentlandite as the main nickel bearing sulphide and pyrrhotite is the dominant sulphide gangue mineral, the deposit was hosted in a mixture of ultramafic and felsic rock.

Disseminated sulphide ore

At the completion of the massive sulphide deposit a larger lower grade disseminated ore body was developed. At this point the processing plant was expanded and modified to accommodate the new lower grade ore. A tertiary crushing stage was added and a new primary ball mill and rougher/scavenger circuit was installed. The original circuit was converted for concentrate regrinding and cleaning with the addition of 1 extra tank cell to increase flotation capacity. The concentrate regrind circuit consisted of the original single stage ball mill in closed circuit with a cyclone cluster. The magnetic conditioning unit was installed on the regrind cyclone overflow stream to determine the effectiveness on disseminated ore.

At the conclusion of a successful trial period it was decided to install an additional magnetic conditioning unit at the head of the primary rougher/scavenger circuit. Mineralogy of the disseminated sulphide ore consisted of pentlandite as the main nickel bearing sulphide and pyrrhotite/pyrite as the dominant sulphide gangue minerals. Sulphides were relatively fine grained and hosted in an ultramafic host rock.

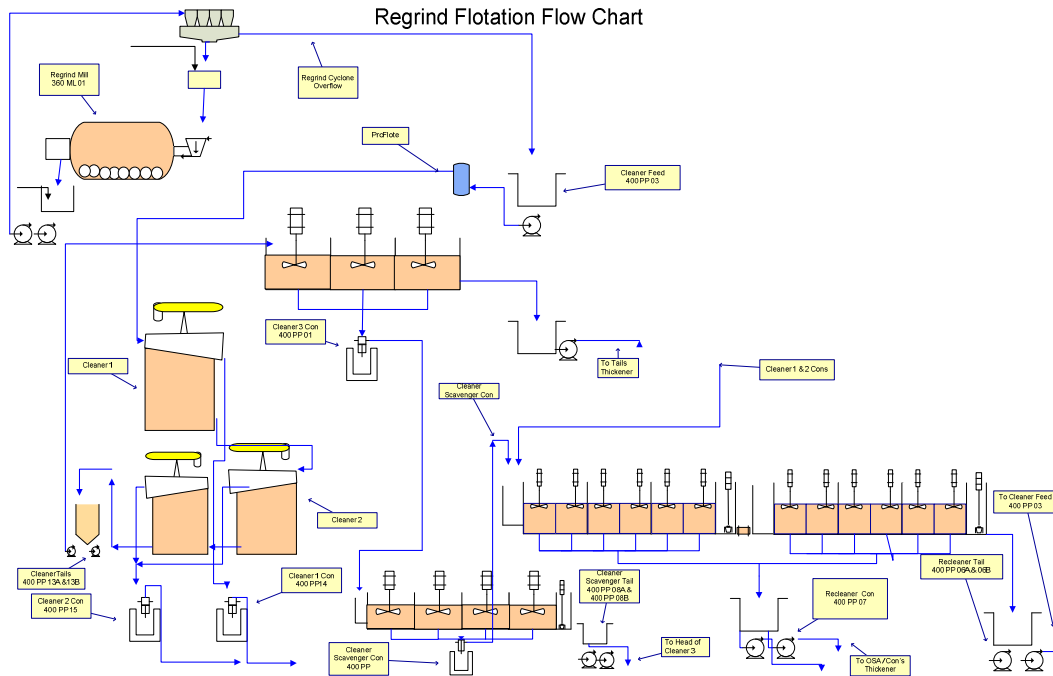


Fig.2. Regrind flotation flowchart for disseminated ore

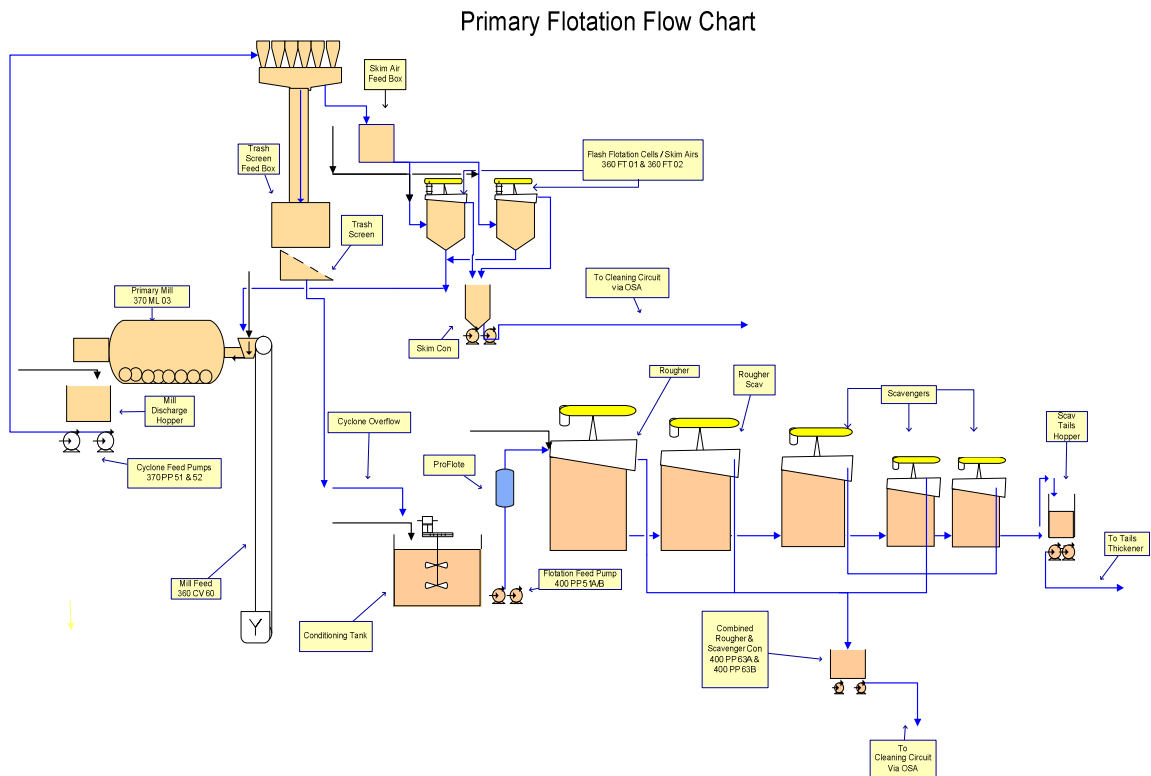


Fig. 3. Primary flotation flowchart for disseminated ore

METHOD

The magnetic conditioning device was installed in the flotation streams as indicated.

The device was turned ON or OFF; this was randomised with respect to the plant operation. Automatic plant samples were taken and analysed. For the testwork on the disseminated ore the tails samples only were sampled and the samples sized at 38µm and also at 20µm and the sized samples analysed for nickel.

RESULTS AND DISCUSSION

Magnetic conditioning in a pentlandite rougher circuit – massive sulphide ore

The typical cyclone overflow was 1.5% nickel, 14% iron and 10% magnesium oxide. The daily alternating ON-OFF test operated for about four months. The primary ore was processed in three campaigns during this period. The mean results and the statistical analysis for the three periods are summarised in Tables 1 and 2.

Table 1

Mean results for rougher test of magnetic conditioning

	% Ni feed	% Ni tail	% Ni conc	% Ni rec
Magnetic conditioning ON	1.43	0.35	14.94	76.81
Magnetic conditioning OFF	1.46	0.38	14.88	75.96

A paired analysis was carried out comparing the ON and OFF data for the three periods. The statistical results are in Table 2.

Table 2

Statistical analyses of rougher results

	% Ni in tail	% Ni recovery
Magnetic conditioning ON	0.35	76.81
Magnetic conditioning OFF	0.38	75.96
Difference	0.03	0.85
”t” value	3.50	6.38
Level of confidence	96.4	98.8

The results showed a mean difference of 0.85% in the paired nickel recovery with the level of confidence of 98.8%. The mean difference for the paired nickel assay in tail results was 0.03% nickel at a level of confidence of 96.4%. This is approximately 8% less nickel in the tail.

Plant surveys show that only about 40% of the nickel is present in the <38µm fraction, and assuming, as all other data shows, that magnetic conditioning only effects <38µm recovery, there is a strong indication that the increase in recovery in this ultrafine fraction is about 2% (0.85/40x100).

There was no loss in selectivity, with no effect on the nickel grade of the concentrate with magnetic conditioning. There was also no increase in iron or magnesium oxide in the concentrate. Magnetic conditioning is giving greater selectivity and an improved nickel grade-recovery response – higher recovery at the same concentrate grade.

There was a noted reduction in the nickel distribution in the <38µm fraction of the tail and an increase in the <38µm nickel distribution in the concentrate.

Magnetic conditioning on a disseminated ore – cleaner flotation

The feed and concentrate streams in the cleaner circuit were problematic to sample. Only the cleaner tail could be easily and automatically sampled. Because only the tail could be sampled it was decided that the best way to monitor the affect of magnetic conditioning was to look at the proportion of <38µm nickel in the cleaner tail to determine whether this was reduced when magnetic conditioning was operating. It was concluded that since the size distribution from the regrind was constant, and the nickel distribution across the sizes was also generally constant, the most efficient method to measure the effect of magnetic conditioning was to look at the nickel distribution in the cleaner tail. The advantage of nickel distribution as opposed to nickel assay was the much lower variance for distribution compared to assay. Nickel in tail assay may have been a superior measure if the nickel in cleaner feed was available. The circuit was tested over sixty-nine days with the ON and OFF being randomised. The results are given in Table 3.

Table 3
Magnetic conditioning results in the cleaner circuit

	Ni distribution in cleaner tail	
	<38µm	<20µm
Magnetic conditioning ON	65.22	61.00
Magnetic conditioning OFF	69.28	64.95
Difference	4.06	3.95
"t" value	2.05	1.92
Level of confidence	97.8%	97.0%

The results demonstrate that the magnetic conditioning is reducing the proportion of nickel in the two tail fractions, the <38µm fraction and the <20µm fraction. For both fractions the reduction in the nickel distribution is about 4% absolute with magnetic conditioning and for both fractions the level of confidence is around 97%. Nickel in tail showed a similar result of a similar magnitude but had much higher variance and lower level of confidence.

An estimate can be made of the increase in recovery that this reduction in <38µm nickel in the tail represents. Based on the work by Rivett *et al*, (2007) it can be assumed that magnetic conditioning has no affect on the >38µm nickel recovery. Without magnetic conditioning, every 100g of >38µm nickel in cleaner tail has 225.5g of <38µm (100x69.28/30.72). Assuming no effect on >38µm nickel recovery with magnetic conditioning, the magnetically conditioned tail contains 187.5g (100x65.22/34.78) of <38µm nickel for every 100g of >38µm nickel. The same quantity of cleaner tail then has 325.5g of nickel when magnetic conditioning is OFF

and 287.5g of nickel when magnetic conditioning is ON, or 10.9% less total nickel in cleaner tail. Therefore, depending on the total nickel recovery in the cleaner circuit, the magnetic conditioning is reducing the nickel content in the tail by 10.9%.

Magnetic conditioning on a disseminated ore – rougher flotation

Following the improvement in recovery of ultrafine pentlandite when magnetic conditioning was installed in the new cleaner circuit, magnetic conditioning was tested in the new rougher-scavenger circuit on the feed to the rougher bank.

The rougher-scavenger tail automatic sampler sample was sized at 38µm and 20µm and the size fractions assayed. The testwork was undertaken over 84 days. The results are given in Table 4.

Table 4
Magnetic conditioning results in the rougher-scavenger circuit

	Ni Distribution in scavenger tail	
	<38µm	<20µm
Magnetic conditioning ON	35.06	30.13
Magnetic conditioning OFF	36.96	31.43
Difference	1.90	1.30
”t” value	1.81	1.32
Level of confidence	96.3%	90.6%

Once again, magnetic conditioning reduces the proportion of fine nickel in the scavenger tail. For the <38µm fraction there is 1.90% less nickel in the tail when magnetic conditioning is operating, to a level of confidence of 96.3%. The difference in the <20µm fraction is 1.30% less nickel to a level of confidence of 90.6%. It is surprising that the effect of magnetic conditioning appears smaller in the finest fraction. There is no obvious explanation for this; it is contrary to the cleaner testwork and all the previous testwork.

The nickel in tail assay showed a slightly larger difference in magnitude with the magnetic conditioning compared to the nickel distribution, but like the cleaner testwork the variance was much higher, and so the level of confidence lower.

An estimate can be made of the increase in recovery that this reduction in <38µm nickel in the tail represents. Based on the work by Rivett *et al.*, (2007) it can be assumed that magnetic conditioning has no affect on the >38µm nickel recovery. Without magnetic conditioning, every 100g of >38µm nickel in rougher-scavenger tail has 58.6g of <38µm (100x36.96/63.04). Assuming no effect on >38µm nickel recovery with magnetic conditioning, then the magnetically conditioned tail contains 54.0g (100x35.06/64.94) of <38µm nickel for every 100g of >38µm nickel. The same quantity of tail has 158.6g of nickel when magnetic conditioning is OFF and 154.0g of nickel when magnetic conditioning is ON, or 2.9% less total nickel in rougher-scavenger tail. Therefore, depending on the total nickel recovery in the rougher-scavenger circuit, the magnetic conditioning is giving 2.9% less nickel in the tail than no magnetic conditioning

For a 75% nickel recovery in the rougher-scavenger circuit this represents a 0.73% increase in total nickel recovery. This result is very similar to the 0.85% increase in nickel recovery in the original testing of magnetic conditioning on the massive sulphide ore (with a total nickel recovery of about 77%).

The magnetic conditioning is not giving as large an improvement in the rougher-scavenger circuit as in the cleaner circuit (a similar observation to the one made by Bott and Lumsden 2009). This may be due to a lower nickel concentration in the rougher scavenger feed or it may be due to the lower residence time in the magnetic field, similar to the possible reasons given by Bott and Lumsden (2009).

CONCLUSION

Plant testing of a pentlandite ore has shown that magnetic conditioning of the froth flotation feed increases the fine nickel recovery. For rougher-scavenger flotation the increase was found to be in the order of 0.85% increase in total nickel recovery at the same nickel concentrate grade. In the cleaner circuit there was a decrease of total nickel in tail of 10.9%. The test results showed that even where there was a high concentration of strongly paramagnetic minerals magnetic conditioning still selectively increased the pentlandite recovery.

A novel method of running a plant trial was employed where only the nickel distribution of the tail stream was measured. While a large number of data points were required to achieve high levels of statistical confidence using this method, nevertheless, high levels of confidence were achieved, validating the methodology.

ACKNOWLEDGEMENTS

Barry Lumsden would like to thank Professor Jameson of the University of Newcastle for his support of his research work.

REFERENCES

Ahmed, N. and Jameson, G., The effect of bubble size on the rate of flotation of fine particles. *International Journal of Mineral Processing*, 1985, **14**, 196-215.

Ahmed, N. and Jameson, G., Flotation kinetics. *Mineral Processing and Extractive Metallurgy Review*, 1989, **50**, 77-99.

Andres, U., *Magnetohydrodynamic and Magnetohydrostatic Methods of Mineral Separation*. 1976, Wiley, New York.

Blackwell, K. Clark, I. Stockton, N. and Warren, L., Recovery of ultrafine pentlandite by shear-flocculation. In *Proc. of the Int Conf Extractive Metallurgy of Gold and Base Metals*, AusIMM, Kalgoorlie, 1992, pp. 247-251.

Bott, A. and Lumsden, B. Magnetic conditioning at the Hellyer tailings retreatment plant. In *Proc. of the Tenth Mill Operators' Conference*, AusIMM, Melbourne, 2009, pp. 247-254.

- Dobby, G. and Finch, J., Particle size dependence in flotation derived from a fundamental model of the capture process. *International Journal of Mineral Processing*, 1987, **21(3-4)**, 241-260.
- Duan, J. Fornasario, D. and Ralston, J., Calculations on the flotation rate constant of chalcopyrite particles in an ore. *International Journal of Mineral Processing*, 2003, **71**, 227-237.
- Engelhardt, D. Ellis, K. and Lumsden, B., Improving fine sulphide mineral recovery – plant evaluation of a new technology. In *Proc. Centenary of Flotation Symposium*, AusIMM, Melbourne, 2005, pp. 829-834
- Fuerstenau, D. Chander, S. and Abouzeid, A., The recovery of fine particles by physical separation methods. In *Beneficiation of Mineral Fines Problems and Research Needs*, ed. P. Somasundaran and N. Arbiter, The American Institute of Mining, Metallurgical and Petroleum Engineers, Inc, Littleton, 1979, pp. 3-61
- Gaudin, A. and Rush Spedden, H., Magnetic separation of sulphide minerals. *AIME Transactions*, 1943, 153:563
- Holloway, B. Clarke, G. and Lumsden, B., Improving fine lead and silver flotation recovery at BHP-Billiton's Cannington mine. In *40th Annual Meeting of the Canadian Mineral Processors*. Canadian Institute of Mining, Metallurgy and Petroleum, Ottawa, 2008, pp. 347-362.
- Hunt, C. Moskowitz, B. and Banerjee, S., Magnetic properties of rocks and minerals. In *Rock Physics and Phase Relations, A Handbook of Physical Constants*. ed. T. Aherns. American Geophysical Union, 1995, pp. 189-204.
- Jameson, G. Nguyen, A. and Ata, S., The flotation of fine and coarse particles. *Froth Flotation a Century of Innovation*. ed. M. Fuerstenau, G. Jameson and R. Yoon. Society for Mining, Metallurgy and Exploration Inc., Littleton, 2007, pp. 339-372.
- Lu, S. Song, S. and Dai, Z., The hydrophobic and magnetic combined aggregation of paramagnetic minerals. In *XVI International Mineral Processing Congress*. ed. E. Forssberg, Elsevier, Amsterdam, 1988, pp.999-1009.
- Peng, Y. Cotnoir, D. Ourriban, M. Richard, D. and Liu, Q., Some solutions to the problems in fine particle flotation. In *Proc Centenary of Flotation Symposium*, AusIMM, Melbourne, 2005, pp.535-540.
- Rivett, T. Wood, G. and Lumsden, B., Improving fine copper and gold flotation recovery – a plant evaluation. In *Proc of the Ninth Mill Operators' Conference*, AusIMM, Melbourne, 2007, pp. 223-228.
- Rubinstein, J. and Barsky L., *Non-ferrous ores: deposits, minerals and plants*. Taylor and Francis, London, 2002.

- Skvarla, J. and Zelenak, F., Magnetic-hydrophobic coagulation of paramagnetic minerals: a correlation of theory and experiments. *International Journal of Mineral Processing*, 2003, **68**, 17-36.
- Song, S. Lopez-Valdivieso, A. Reyes-Bahena, J. Bermjo-Perez, H. and Trass O., Hydrophobic flocculation of galena fines in aqueous suspensions. *Journal of Colloid and Interface Science*, 2000, **227**, 272-281.
- Song, S. Lopez-Valdivieso, A. Reyes-Bahena, J. and Bermjo-Perez, H., Hydrophobic flocculation of sphalerite fines in aqueous suspensions induced by alkyl xanthate. *Colloids and Surfaces A: Physicochemical Engineering Aspects*, 2001, **181(1-30)**, 159-169.
- Song, S. Lopez-Valdivieso, A. Reyes-Bahena, J. and Lara-Valenzuela, C., Flocculation of galena and sphalerite fines. *Minerals Engineering*, 2001, **14(1)**, 87-98.
- Svoboda, J., *Magnetic Methods for the Treatment of Minerals*, Elsevier, Amsterdam, 1987.
- Torrise, C. and Smith, R., Bringing split float to reality – the Cannington experience. In *Proc. Eighth Mill Operators' Conference*, AusIMM, Melbourne, 2003, pp. 73-80.
- Yalcin, T. Sabau, A. and Wells, P., Magnetoflotation of nickel ore. *CIM Bull*, 2000, **93**, 97-102.