IMPROVING FINE SULPHIDE MINERAL RECOVERY AT THE RED DOG OPERATION

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ABSTRACT

Red Dog is one of the world's largest zinc producing mines and a significant producer of lead and silver. While some of the operational challenges relate to the mine's location in a remote part of Alaska, there are also challenges in the mineral separation process. Recent processing upgrades have included the installation of two M5000 IsaMills to improve the zinc regrind circuit and of one Jameson Cell to improve the pre-flotation circuit. Relatively fine grinding is required to achieve efficient mineral separation at Red Dog, but while fine grinding aids in the production of high grade concentrates, it also creates challenges in the efficient recovery of fine minerals. Over half of the lead lost to the lead circuit tailings, as well as almost half of the zinc lost to the final tailings, is in the finer size fractions (<10 µm). The high pulp density experienced in the pre-flotation and lead rougher circuits also causes significant entrainment loss of lead and zinc to the pre-flotation concentrate and of zinc to the lead concentrate. To help improve fine mineral recovery, Red Dog has recently plant tested and installed magnetic conditioning technology in the flotation circuits. The equipment aggregates fine paramagnetic sulphides and selectively increases their flotation recovery. This paper outlines the testing and positive results at Red Dog.

KEYWORDS

Fine, Sulphide, Flotation, Magnetic, Conditioning

INTRODUCTION

Red Dog is the largest zinc mine in North America and represents approximately 29% of North American zinc concentrate production. The mine is located in northwest Alaska, approximately 100 miles north of the Arctic Circle and 50 miles inland from the Chukchi Sea. The remote location makes the mine accessible only by air or seasonally by ocean-going barges. Red Dog is a partnership between NANA Regional Corporation Inc, the land owner and Teck Alaska Incorporated, the operator of the mine.

Red Dog Ore and Mineralogy

The Red Dog deposit is a rich sedimentary exhalative (sedex) zinc-lead-silver deposit. The main minerals present in order of abundance are: quartz, sphalerite, pyrite, barite and galena. Production began in 1989 with mining of the Main deposit. Between 1989 and 2012, approximately 55.6 million tonnes of ore with an average grade of 20.5% Zn, 5.6% Pb, and 97 g/t Ag was mined from the Main deposit. Subsequent to the development of the Main pit reserve, two additional open pit deposits were discovered: Aqqaluk and Qanaiyaq. The first blast in Aqqaluk occurred on June 4, 2010. As of December 31, 2014, the Aqqaluk deposit reserve is an estimated 45.7 million tonnes of ore with an average grade of 15.1% Zn, 3.9% Pb and 71 g/t Ag.

Red Dog Flotation Circuit

A schematic of the Red Dog flotation circuit is shown below in Figure 1. The ore is ground to 80% passing 75 µm prior to flotation. Flotation consists of three sequential stages; pre-flotation to remove naturally floating organic carbon and elemental sulphur, lead flotation and zinc flotation. The flotation equipment consists primarily of $50m^3$ tank cells for both roughing and cleaning and columns for final cleaning. Regrinding is done with two (2) 335 kW tower mills in the Pb circuit and with two (2) M5000 IsaMills in the Zn circuit.

The concentrate from the pre-flotation stage is discarded directly to tailings. The pre-flotation tailings feed the Pb rougher circuit. The Pb final concentrate is produced through four (4) 2.74m and one (1) 4.11m flotation columns. The lead rougher tailings feed the zinc rougher circuit. The Zn 1^{st} rougher concentrate and the reground Zn 2^{nd} rougher concentrate feed the three stage Zn cleaner circuit. Final concentrate from the Zn cleaner circuit is produced via six (6) 3.66 m flotation columns. The reground Zn cleaner tailings feed the Zn retreat circuit which also consists of three cleaning stages. Final concentrate from the retreat section is produced by two (2) 3.66m flotation columns. The 1^{st} retreat tailings are directed to final tailings.

Magnetic Conditioning

In sequential, selective, sulphide flotation fine sulphide minerals are misplaced either to tails because of their poor collision efficiency with bubbles (Duan, Fornasario & Ralston, 2003), or recovered unselectively by entrainment in the preceding concentrate. As mineral size increases the efficiency of particle-bubble collision increases and recovery by entrainment is reduced (Trahar, 1981). Therefore, selective aggregation of fine sulphide minerals should increase the selective recovery of fine minerals to the desired concentrate while reducing the misplacement of fine sulphide mineral by entrainment in the undesired concentrate.

Magnetic conditioning has been shown at many sites to increase the recovery of fine paramagnetic minerals by selective aggregation of these paramagnetic minerals. (Engelhradt, Ellis & Lumsden, 2005; Musuku, Muzinda & Lumsden, 2015; Rivett, Wood & Lumsden, 2007: Wilding & Lumsden 2011). Where multiple paramagnetic sulphide minerals are recovered by sequential flotation, testwork has shown selective recovery increases and entrainment losses decline. This has been demonstrated in chalcopyrite-sphalerite flotation circuits (Aslan, Hassoy, Boz, Lumsden & Geredeli, 2010; Wilding & Lumsden 2011)

and in chalcopyrite-pentlandite circuits (Musuku et al, 2015), where copper recovery is increased and sphalerite or pentlandite losses are reduced.

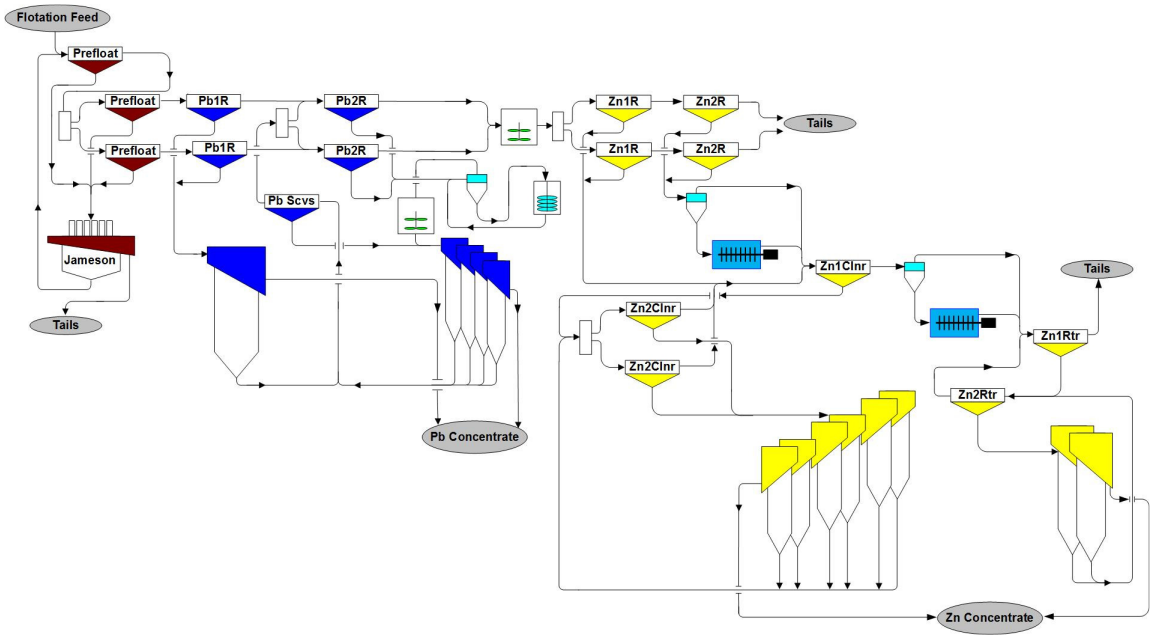

Figure 1 - Red Dog flotation circuit

The Red Dog flotation circuit is a selective sequential flotation of galena followed by sphalerite. While galena is generally found to be diamagnetic, some galena can be paramagnetic, probably due to the inclusion of iron in the galena. The Red Dog galena was measured to be paramagnetic. This was also found for the galena at Cannington in Australia (Holloway, Clarke & Lumsden, 2008). The Red Dog sphalerite mineral composition is on average 63.6 % zinc, 32.9% sulfur and 3.5% iron. Typically, for most natural sphalerite, the iron is substituted for zinc in the sphalerite lattice giving this natural sphalerite a paramagnetic susceptibility (Svoboda, 1987). The Red Dog sphalerite was also measured to be paramagnetic. This gave increased opportunities to evaluate the magnetic conditioning in both the lead and the zinc circuits. The magnetic susceptibility of the galena and sphalerite concentrate is given in Table 1.

Table 1 – Magnetic susceptibility of Red Dog concentrates

	Pb Con	Zn Con
Magnetic Susceptibility x 10^{-9} m^3kg^{-1}	1072	347

Plant Evaluation of Magnetic Conditioning

Paramagnetic minerals will magnetise and aggregate if they are magnetised by a magnetic field but it is necessary to measure the quantitative effect on the flotation recovery of paramagnetic sulphides so as to answer the question, 'Is the change in flotation grade-recovery economically beneficial to the plant?' Only a statistical plant test can answer this question. The preferred statistical test is the paired t test because it reduces the effect of ore and plant variability (Napier Munn, 2010). The details and results of the initial Red Dog ProFlote magnetic conditioning test were published by Oliver, Lacouture and Lumsden (2016).

In selecting the locations for the testwork it was critical to identify where fine paramagnetic galena and sphalerite minerals were lost. Initial testwork was in the zinc circuit because the value of zinc in Red Dog ore is about four times the value of the lead. The zinc retreat circuit was identified as the ideal

first location to trial the ProFlote equipment for two reasons. Firstly, Engelhardt et al. (2005) and others have shown that magnetic aggregation can selectively increase recovery of less than 38µm sphalerite mineral. Surveys of the zinc retreat circuit at Red Dog showed that approximately 75% of the sphalerite loss in the 1st retreat tailings is fully liberated less than 38µm sphalerite. For comparison, only about 50% of the zinc rougher tailings are finer than 38 µm making the retreat circuit the preferred location. Secondly, it is desirable to increase the recovery in the 1st retreat circuit as these tailings report to final tailings and there is no opportunity for recovery again downstream. Therefore, nine ProFlote units were installed in the zinc 1st retreat circuit: five units in the first flotation cell and four units in the second flotation cell.

After the initial success in the retreat circuit a second stage of testwork was initiated. This zinc retreat circuit testwork has shown that there was a slight increase in lead recovery to the zinc concentrate, indicating that lead flotation was amenable to magnetic conditioning. While the increase was small, nevertheless, it was to a reasonable level of confidence and consistent with the measurement of the paramagnetism of the galena.

The first stage of flotation at Red Dog is a collector-less flotation of carbonaceous pyrite to a pre-flotation concentrate that reports to the final tailings. There is fine liberated galena and sphalerite lost by entrainment to the pre-flotation concentrate. The second plant evaluation was to install the magnetic conditioning in the pre-flotation circuit with the aim of reducing entrainment loss in the pre-flotation stage, reduce zinc entrainment in the lead concentrate and then subsequently increase lead recovery to the lead concentrate and zinc recovery to the zinc concentrate. At the same time, additional ProFlote units were installed in the lead cleaner scavenger circuit where fine lead was lost.

EXPERIMENTAL

The results for each shift were measured and the plant recoveries calculated for each circuit based on assay results from routine automatic plant samples. The differences in the recovery and grade between the ON and OFF members of a pair were compared. Two different methods were used to pair the data. For the first method, all of the trial data was used and paired as show below.

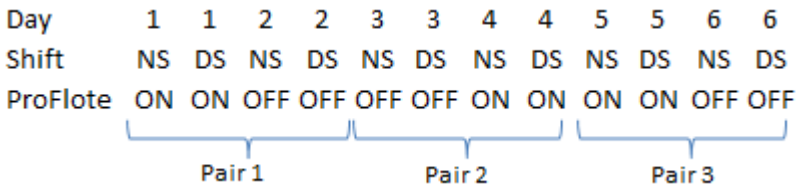

Figure 2 – ON/OFF pairs using all data

For the second method, the first shift after the ProFlote units were switched between ON or OFF was considered an equilibrium shift and was excluded from the data. This was done as there was a concern that the effect of ProFlote may be masked by the long residence time in the retreat circuit and the consequent mixing of the ON and OFF results during this equilibrium shift. As shown below in Figure 3, the data was paired by taking the mean of the three data points excluding the equilibrium shift and then pairing with the mean of the following three data points again excluding the equilibrium shift.

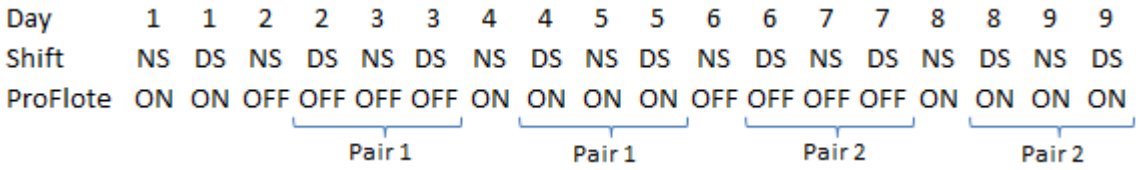

Figure 3 – ON/OFF pairs with 12 hour lag period

The obvious disadvantage of this lag method is the reduction in the number of ON/OFF pairs for comparison. The first method gives four pairs over an eight day period, whereas the second method only gives two pairs over eight days.

RESULTS AND DISCUSSION

Test 1: Zinc Retreat Circuit Test

The results from the four month plant trial were statistically analyzed using the paired t test. The results for the overall zinc circuit are shown below in Table 2 and Table 3.

Table 2 – Paired t test results for total Zn circuit

	%Zn Rec	%Zn Grade
ON	85.2	56.2
OFF	84.5	56.0
Difference	0.7	0.2
No of pairs	47	47
Confidence	96%	95%

Table 3 – Paired t test results for total Zn circuit with 12hr lag period

	%Zn Rec	%Zn Grade
ON	85.4	56.1
OFF	84.3	56.1
Difference	1.1	0
No of pairs	24	24
Confidence	98%	Low

The results in Table 2 and Table 3 are mutually consistent. Both show an increase in zinc recovery to a high level of confidence at equal to higher concentrate grade, demonstrating that with ProFlote online, an improvement in the grade recovery curve is achieved. Also, the fact that the difference in recovery is greater in Table 3 as compared to Table 2 suggests that the concern identified before the start of the trial, that an equilibrium period is required between the times when the magnets are varied between the ON and OFF positions in order for the full benefit to be observed, is true.

The lead recovery to zinc concentrate during this initial zinc retreat test are in the Table 4.

Table 4 – Paired t test results for Pb recovery to Zn conc

	%Pb Rec to Zinc Conc
ON	17.7
OFF	17.3
Difference	0.4
No of pairs	47
Confidence	90%

Test 2: Pre-flotation and Lead Scavenger Test

With magnetic conditioning in both the pre-flotation and the lead scavenger, the results in Table 5 were achieved, employing a paired t test.

Firstly, the recovery of zinc to zinc concentrate increased by 0.8% and the zinc in the final tailings was reduced by 0.22%; both of these results are to greater than 99% confidence. The lower zinc in final tailings could be due partly to lower entrainment losses in the pre-flotation concentrate resulting in higher zinc recovery to the zinc concentrate, but it is predominantly due to better zinc flotation in the zinc circuit. While with magnetic conditioning there was equal recovery of zinc to the lead concentrate, this improvement in Pb:Zn selectivity in the lead circuit (higher lead recovery at the same zinc recovery) could not have contributed to the improvement in zinc recovery to the zinc concentrate. The higher zinc recovery at equal zinc concentrate grade shows an improved Zn grade-recovery response with magnetic conditioning to a very high level of confidence.

Table 5 – Paired t test results for Zn circuit recovery

	%Zn Rec	%Zn Grade	%Zn Final Tailings
ON	85.4	55.5	2.46
OFF	84.6	55.6	2.68
Difference	0.8	0.1	0.22
No of pairs	45	45	45
Confidence	99%	low	99%

Similar results were achieved looking at the 12 hour lag results but because this method has fewer pairs the level of confidence was not as high as with the no lag period.

The lead flotation results were more complex to understand. While for all ores there was an increase in lead recovery of about 0.6% at about 95% confidence, it was noted that the lead results were substantially better on the normal Red Dog ore that predominates. For the predominant fine grained Red Dog ore, Table 6 shows that there was an increase in lead recovery at the same lead concentrate grade, as well as a reduction in lead in final tailings. The increase in lead recovery and reduction in lead to final tailings are to a high confidence.

Table 6 – Paired t-test results for Pb circuit recovery

	%Pb Rec	%Pb Grade	%Pb Final Tailings
ON	66.7	55.3	1.37
OFF	65.7	55.3	1.43
Difference	1.1	0.0	0.06
No of pairs	34	34	34
Confidence	99%	Low	99%

The result is showing that on this predominant ore, ProFlote magnetic conditioning is achieving an improved Pb grade-recovery curve. The ore type was not so important with the zinc circuit results. Again, as in the zinc circuit, it cannot be clearly identified the primary cause of the increase in lead recovery, whether due to a reduction in lead entrainment losses to the pre-flotation concentrate or due to an increase in aggregated galena recovery in the lead circuit. Most probably the better lead recovery is primarily because of improved lead flotation in the lead circuit. There was a reduction in lead in lead cleaner scavenger at about 88% confidence, but because of the variability more data would have needed to be collected to determine whether this was significant.

Nevertheless, the ProFlote magnetic conditioning is giving a 1.9% increase in combined lead and zinc recovery to very high levels of confidence. Moreover, this is a selective increase with better lead-zinc selectivity in the lead circuit and no loss in metal concentrate grades at these higher metal recoveries.

ECONOMICS

Most plants operate to maximize recovery at the concentrate grade required by the smelter contract. However, there are benefits of lower treatment and transport costs for higher concentrate grades. Since the grade recovery outcome in a plant varies due to both process variation and more significantly due to ore variation within the same ore-body, the relationship between grade and recovery between two data sets cannot be metallurgically combined to give a single measured metallurgical benefit. For instance, if a plant change gives a 1% increase in recovery at a 0.5% lower concentrate grade is that just a move along the same grade-recovery curve, or is it a better (or worse) grade recovery curve? Long, Taylor and Lumsden (2012) studied this problem but utilized a financial, rather than metallurgical approach and developed a method to statistically combine the grade and recovery benefit of two test data sets by analyzing the economic benefit based on the results from the ON/OFF plant trial. The method combines changes in concentrate grade and recovery for each pair to give a single financial value for the grade-recovery outcome that can be compared and analyzed by a paired 't' test. The financial modelling is carried out using a ratio of the relative financial benefit of an increase in zinc concentrate grade and zinc recovery to zinc concentrate. This method was tested on some ProFlote plant trial data and found to give a good statistical comparison.

Using generic values for smelter terms, transport costs and current metal prices the zinc grade and recovery results can be combined according to the method of Long et al. (2012). Based on this financial comparison between zinc grade and zinc recovery and using the grade and recovery data for each day from the initial test, the economic outcome for each on and off pair can be calculated, and a statistical analysis using the paired t test can be undertaken. The result is shown in Table 7. The results for both methods of pairing the grade and recovery data, with and without a lag period, are included.

The results in Table 7 show that to a very high level of confidence, the ProFlote technology provides a significant economic benefit to Red Dog. While the key result is the high level of confidence in the beneficial financial outcome, the results also demonstrate how recovery is a much bigger driver of

financial outcomes than concentrate grade. While both results give about a 1% increase in Zn grade and recovery the greater recovery benefit with the lag method results in about a 50% increase in financial benefit to Red Dog.

Table 7 – Financial benefit (USD/day) of ProFlote installed in the Zn retreat circuit

	Overall Zn Circuit	Overall Zn Circuit - 12hr lag
Increase (USD/day)	23,420	34,200
't'	2.0	2.3
No of pairs	47	25
Confidence	98%	98%

For the pre-flotation test it is also possible to combine the financial benefits of the increase in lead recovery and zinc recovery and calculate using generic metal prices and treatment values the statistical confidence and value of these benefits, and these results are given in Table 8. However, because the concentrate grades are similar for both the lead and zinc results, grade doesn't add to the financial benefit.

Table 8 – Financial benefit (USD/day) of ProFlote installed in the pre-flotation circuit

	Overall Pb Circuit	Overall Zn Circuit	Combined
Increase (USD/day)	3,400	14,100	17,200
't'	1.7	2.9	3.1
No of pairs	47	47	48
Confidence	95%	99%	99%

For the Aqqaluk pit to date, the proportion of the predominant (or fine grained) ore has been above 90% of the feed. The financial benefit of ProFlote magnetic conditioning to the overall lead circuit, when processing the predominant ore, can also be calculated, and is summarized in Table 9.

Table 9 – Financial benefit (USD/day) of ProFlote installed in the pre-flotation circuit – predominant ore

	Overall Pb Circuit
Increase (USD/day)	6,400
't'	2.9
No of pairs	34
Confidence	99%

While this method combines and statistically compares the overall financial difference for multiple parameters, like grade and recovery, it does not include the cost differences. For magnetic aggregation the costs are not variable but the same for every ON day, therefore, this fixed cost difference, compared to OFF, can be deducted from the mean difference from the statistical analysis that compares the variable differences. In the case of magnetic aggregation the cost of equipment, maintenance and utilities is low, generally less than 10% of the benefit and so has little impact on the economics.

CONCLUSIONS

Based on the results from statistical plant trialing it can be concluded that at a high level of confidence, ProFlote is selectively increasing the plant metallurgy at Red Dog. With ProFlote online, an increase in zinc recovery or zinc recovery and zinc grade of around 1.7%-1.9% combined has been achieved with both magnetic conditioning installations operating. There has also been an increase in lead recovery of 1.1% on the predominant ore. The resulting economic benefit is substantial and also at a very high level of confidence.

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