Improved mining recovery with bulk ore sorting and MR technology

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ABSTRACT

Sensor-based bulk ore sorting is a form of preconcentration that autonomously measures and physically separates discrete bulk 'pods' of run of mine ('ROM') or primary crushed material. This case study examines the results of a full scale bulk ore sorting trial undertaken at Cozamin mine in Zacatecas, Mexico in 2019. The bulk ore sorting plant comprised primarily of a mobile jaw crusher, fixed conveyor, MR analyser, and diverter gate. Results of the trial demonstrate that bulk ore sorting could deliver a net improvement in copper metal fed to the processing plant of 6-8 per cent within an equal gross tonnage of ore. Copper metal increases were the result of improvements in mining recovery, where valuable mineralisation is recovered from marginal or sub-grade material that would otherwise be discarded as waste or stockpiled as low-grade. The increase in mining recovery more than compensates for metal losses suffered in the bulk ore sorting plant.

INTRODUCTION

Sensor based bulk ore sorting is a form of preconcentration that can deliver high-throughput separation of material between the mine and the processing plant (Duffy, 2015). Measurements are performed by one or a combination of sensing technologies that determine the characteristics of material pods and their corresponding treatment downstream. Sensing technologies for bulk ore sorting are typically penetrative measurement technologies such as magnetic resonance (Coghill, et al., 2018), PGNAA (Kurth, 2017) or PFTNA.

A common misunderstanding of bulk ore sorting is that it is seen to be value destructive based on metal losses. It is argued that while bulk sorting can generate an improvement to process plant feed grade, inevitably some valuable material is rejected and lost. However, modelling and scenario analysis of the Phu Kham mine revealed that the use a bulk ore sorting can lead to a net increase in overall metal production given a fixed plant feed capacity. (W Valery, 2016) In that case study, increases of between 13 and 40 per cent were modelled. These increases were achieved by lowering the mining cut-off grade and bulk ore sorting the larger overall volume of feed material. Any losses from bulk ore sorting were more than compensated by the increase in mining recovery, with supplemental metal processed that would otherwise have been discarded as waste or stockpiled as low grade.

The case study presented in this paper examines a bulk ore sorting trial carried out by Capstone Mining in partnership with NextOre in 2019 which gives practical results of a full scale bulk ore sorting system and which supports the conclusion of the Phu Kham modelling, with results of a potential overall net increase in metal production for a fixed process feed capacity.

Furthermore, analysis of data collected during that trial reveals a high degree of variability on a tonne-by-tonne and truck-by-truck basis. This highly granular grade data frequently differs from grade estimates assigned on larger volumes of in-situ mining inventory, in this case corresponding to a smallest mining unit ("SMU") equivalent to a stope firing or development advance firing. This variability was observed despite average measured and estimated grades reconciling quite closely over all tonnes processed in the trial. Suggesting an operational benefit, in addition to that of simply upgrading ore, can be derived by correcting the assignment of ore and waste.

BULK SORTING

Sensor-based bulk ore sorting systems use sensing technologies to derive a grade estimate for a volume of broken rock and instruct downstream systems on proper treatment. (e.g. Ore, waste, low-grade, or alternative processing streams.) Bulk ore sorting systems are typically installed as early as possible in the mining and processing chain, and so the form of feed material is usually either ROM or primary crushed ore. Terminology varies, but the volume of rock on which measurements are generated and decisions are made is typically referred to as “packets” or “pods” and spans the full range of particle sizes within that volume.

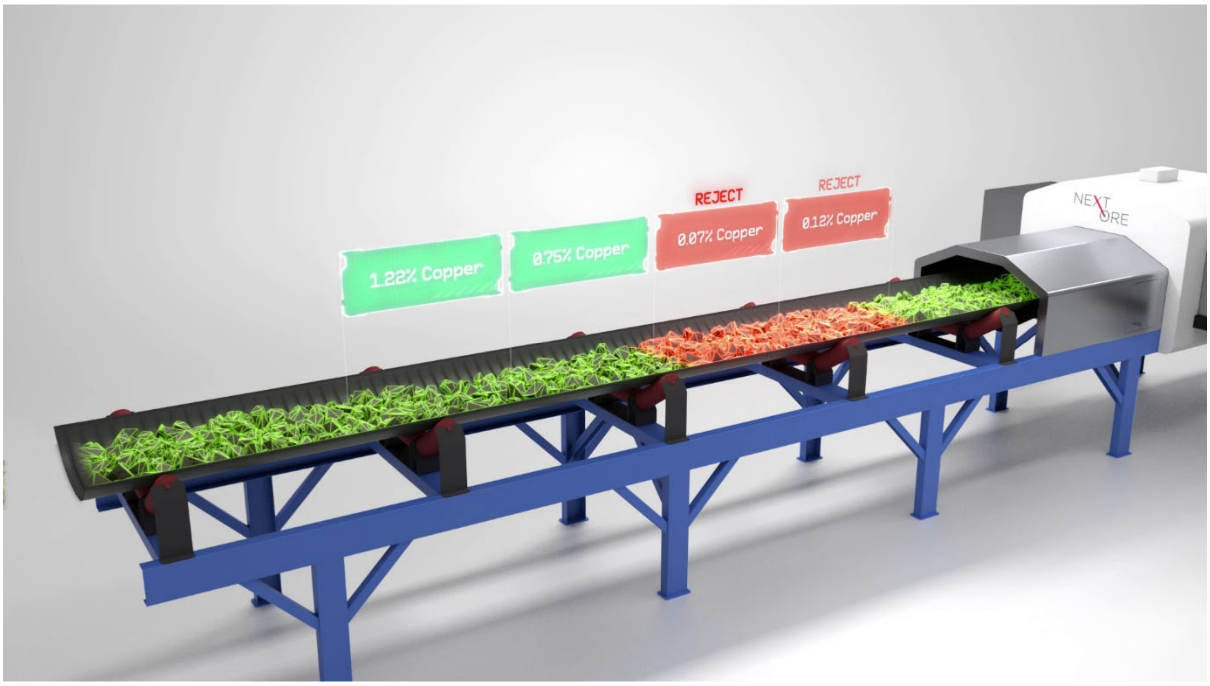

Figure 1 - Grade measurements and sorting destinations assigned on a bulk basis.

Because bulk ore sorting makes decisions on pods of material rather individual particles, sorting performance relies on naturally occurring in-situ grade variability, or heterogeneity, to manifest in a range of ore grades presented to the sensing and sorting system. (Peter Coghill, 2015) Furthermore, bulk sorting also relies on this heterogeneity being preserved despite ore handling, rehandling and other forms of mixing that homogenise the ore prior to the point of sorting.

In-situ heterogeneity is frequently and easily observed in geological drilling. Veining, stockworks, and disseminated mineralisation associated with geological features can visually be observed to vary continuously over the length of a diamond drill core intercepts. For practical reasons, however, mining engineers often treat each SMU of ore as a homogenous mass having a single average grade. Production geologists, process engineers, and metallurgists responsible for ROM stockpile blending programs, on the other hand, are more likely to appreciate the degree of persistent variability.

MAGNETIC RESONANCE SENSING

This case study examines a project whereby magnetic resonance (MR) sensing was used to measure copper grades in chalcopyrite mineral form and make automated bulk ore sorting decisions on a pod-by-pod basis.

MR is a technology that delivers precision mineralogical concentration measurements in real-time for mining applications. MR technology uses relatively low frequency radio below that of commercial 2-way or FM radios to excite minerals at their resonant frequencies and detect the consequential quantitative radio-frequency response. MR technology has a very clean measurement free from mineral or elemental interferences in the rock matrix and is deeply penetrative, fast and accurate without the use of ionising radiation. (Bennett, et al., 2009)

On-conveyor MR analysers are typically tuned for one or two target minerals, depending on the application. Not all minerals can be detected using MR (Table of detectible minerals attached in appendix A). Therefore, the first step in assessing MR bulk ore sorting viability at a mining project is mineralogical characterisation, typically through examination of existing technical reporting and discussions with geologists.

MR bulk ore sorting requires that either:

a) the majority of economically significant minerals occur in a measurable form; or

b) the majority of economically significant minerals have a persistent association with measurable minerals such that a proxy can be used reliably; or

c) operational controls can be put in place to restrict sorting to ore types corresponding with either a or b.

For this case study, operational controls were implemented to ensure that copper rich ores only were delivered to the bulk ore sorting plant, therefore satisfying *c* and *a*.

CASE STUDY

Property description

The Cozamin mine ("Cozamin") is an underground mining operation located in the Zacatecas Mining District of Mexico. Cozamin is 100 per cent owned by Capstone Gold S.A de C.V., a subsidiary of Capstone Mining Corp. (Capstone Mining Corp., 2019)

In 2019 Cozamin mined 1.14 million tonnes of ore at average grades of 1.50 per cent copper, 1.07 per cent zinc and 46.7 g/t silver. Cozamin produces separate copper and zinc concentrates, with silver reporting predominantly to the copper concentrate. 2019 concentrate production was 61 270 dry metric tonnes ("dmt") and 17 297 dmt of copper and zinc concentrate, respectively.

Geology

All mineralization at the Cozamin mine occurs in veins, and stockworks of veinlets. Currently mined mineralization at Cozamin is best described as intermediate sulphidation. The copper-rich intermediate sulphidation mineralization is an early phase that is enveloped, overprinted or brecciated by zinc-rich intermediate sulphidation mineralization. The copper-bearing mineralised veins are inferred to have formed at a higher temperature and are significantly less vuggy than the zinc-rich veins. The predominant mineral assemblage of the copper zone is massive pyrrhotite-pyrite-chalcopyrite with little gangue. Zinc-rich veins also tend to be sulphide rich, like the copper-rich ones, but with slightly more gangue. Ore feed to the processing plant is broadly categorised as either zinc-rich ores from the San Rafael zone and copper-rich ores from the Mala Noche Vein ("MNV") and Mala Noche Footwall Zone ("MNFWZ"). (Capstone Mining Corp., 2019)

Chalcopyrite is the only copper sulphide recognized visually at the Capstone Mine. It occurs as disseminations, veinlets and replacement masses. These masses appear to be fractured and brecciated at intermediate levels in the mine. Mineralization at the MNFWZ is chalcopyrite dominant in contrast to the polymetallic nature of the main MNV.

During the trial, only copper-rich ores were fed to the bulk ore sorting plant. For clarity, in all cases where MR measurement grades are reported, these values represent copper weight percent in the form of chalcopyrite.

Trial

The trial plant was built and commissioned between December 2018 and January 2019. The trial was carried out on surface in an unused laydown area between the mine portal and the processing ROM stockpile. The trial was designed to match existing underground infrastructure in dimensions and capacity in the event it was subsequently installed underground. The sorting plant operated for 3 months between February and April of 2019.

Table 1 - Trial statistics

Item		Trial Results
Measurement performance		
Grade measurement interval	s	2 or 4
Grade measurement resolution (1-sigma)	%Cu	0.023%
Peak feed rate	t/h	199
Pod size	kg	50-150
Sorting performance		
Total feed	t	1 660
Feed trucks	#	124
Average feed grade	%Cu	1.10%
Improved tonnes	t	1 125
Average improved grade	%Cu	1.43%
Rejected tonnes	t	535
Average reject grade	%Cu	0.40%
Proportion rejected	%wt	32%
Diverter cut-off grade	%Cu	0.20% - 1.00%

The bulk ore sorting system trialled is shown in Figure 2. The system comprises primarily of a mobile jaw crusher, fixed conveyor, MR analyser, and diverter gate. Ore was fed by a front-end loader to the mobile crusher, crushed to a target top size of 200mm and then fed to the conveyor. The material was then measured using the MR analyser which automatically instructed the downstream pneumatic diverter chute how to direct pods corresponding to either 2 or 4-second integration times.

Figure 2 - Analyser installation before completing of the feed ramp, showing the hopper, crusher and feeder to the left, analyser and electronics container in the centre and diverter at the end of the conveyor.

Table 2 - Bulk sorting system components

Ref	Description	Ref	Description
A	Vibrating feed bin	F	MR Analyser – Sensor
B	Jaw crusher	G	MR Analyser – Electronics container
C	Scalping bypass	H	Diverter chute
D	Feed conveyor	I	Reject discharge area
E	Main conveyor	J	Upgrade discharge area

The diverter chute was a pneumatically actuated “flop-gate” style diverter, with the edge of the flop gate passing vertically through the flow of the conveyor discharge. Steel abrasion resistant wear plates were affixed to either side of the diverter gate. Typical travel time of the flop gate through load was between 780 – 940 ms, with minimum recharge delay of 1.4 seconds. The diverter chute was customer designed and manufactured locally and was controlled by the MR Analyser electronics.

Mining

The mining method at Cozamin is longitudinal longhole open stope and fill. Ore from development drives and stopes is typically transferred to stockpiles before being loaded into 15 tonne trucks. Mineralized material is either hauled to surface via the Guadalupana ramp or taken to the San Roberto shaft and dumped to the grizzly-crusher system. Hoisted material is transferred to surface trucks and dumped into the ROM stockpile before being fed to the concentrator.

During the bulk ore sorting trial, various configurations of mining and materials handling were used to determine the relative impact of each on sorting performance. Ore was delivered both by hoisting and by direct trucking, as described above. In some tests, ore was loaded directly to trucks from development headings or stopes to eliminate additional mixing from rehandling in underground stockpiles.

On surface, trucks used a “line dumping” method to decrease mixing from rehandle, with a front-end loader collecting material in the reverse direction of line dumping. The hopper of the mobile crusher was typically filled with 2 to 3 buckets of ore at a time to ensure consistent conveyor belt loading.

Figure 3 - Line dumping of ore next to the bulk ore sorting plan and loading of feed to the crusher.

Static Sample Measurement validation

To validate MR grade measurements, 5 samples of variable grade across the cut-off range of 0.00-1.20 per cent were measured in the MR Analyser for a blind measurement test. These samples were presented as bags of approximately 30 kg of rock. They were placed in the MR analyser measurement zone and subsequently sent to be crushed, split, subsampled and assayed by Cozamin and a third-party laboratory company. The blind validation test showed a highly linear relationship between raw MR measurement and conventional assay, with a slope of 0.94 and an R^2 of 0.96 as shown in Figure 4.

Along with the sample measurements a single MR measurement standard comprised of Cozamin concentrate loaded into a long thin cylinder (5 cm diameter) was used. This standard contained 0.366 kg of copper as chalcopyrite evenly distributed over the 1 metre cylinder length. Prior to the blind validation procedure the standard was positioned in the MR measurement zone (~70 cm length along the belt), to provide field calibration confirmation. MR internal calibration involves the determination of one simple proportionality factor between MR signal and copper mass, the measurement of which can be performed just once in the entire validation process.

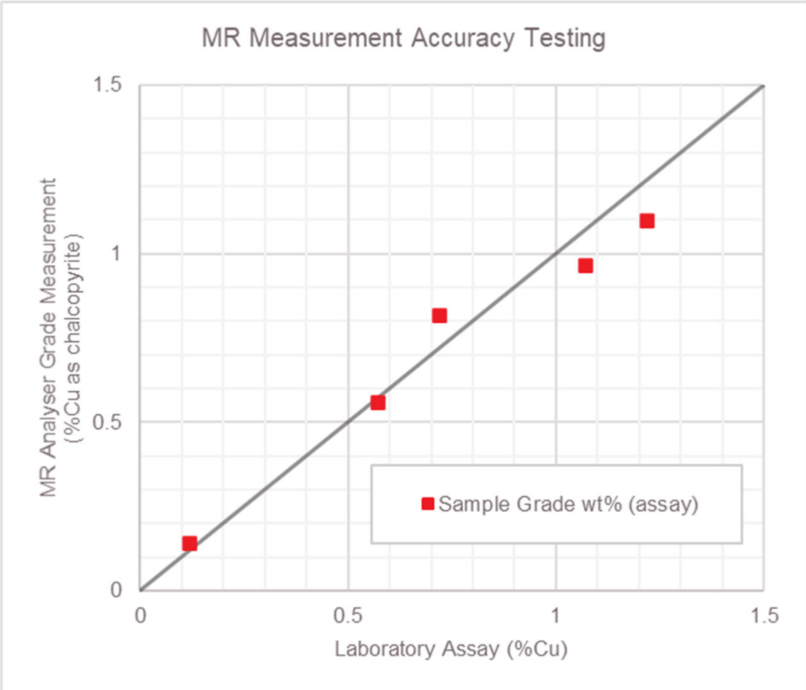

Figure 4 - Results of blind testing to compare MR measurements to laboratory assay.

MINING RECOVERY

Figure 5 shows an example of the distribution of pod grades compiled over a single truckload of ore. In this case, truck #185231 was loaded with 13.0 tonnes of ore at an average estimated grade of 0.70 per cent copper. Once fed to the bulk ore sorting plant, 175 distinct grade measurements were produced for pods weighing 74 kg on average. The average grade of the total truckload as measured by the MR analyser was 0.73 per cent, and so the reconciliation of MR measurements to SMU grade estimate based on average grade was very close. This example shows, though, that a simple grade average disguises the presence of a sizeable distribution of high- and low-grade zones distributed throughout each truck.

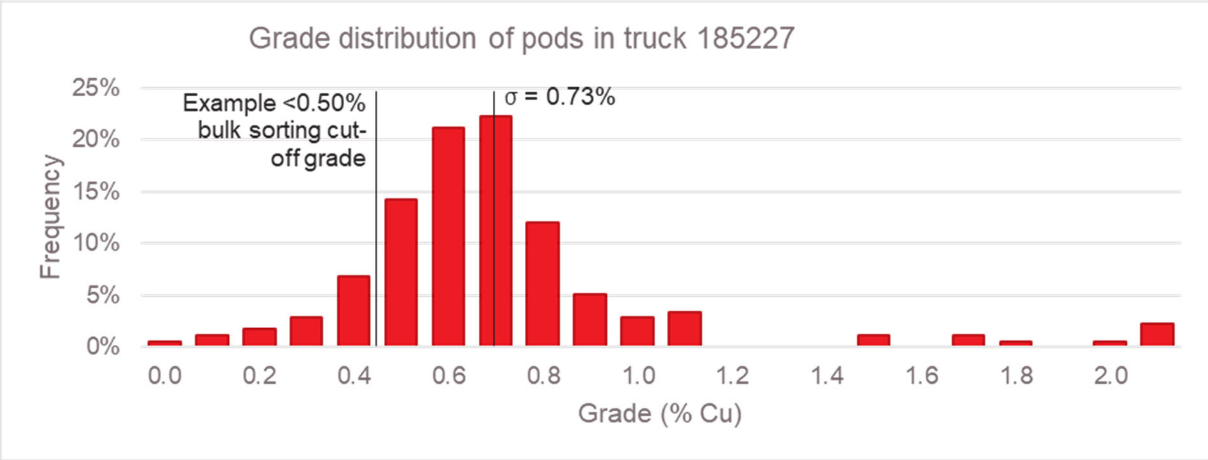

Figure 5 - Grade distribution of pods as measured by the MR analyser for truck 185227, with annotation showing the weighted average copper grade of the total population

Figure 5 can be used to illustrate calculations of bulk ore sorting outcomes. Setting, for example, an arbitrary cut-off as a vertical line over this histogram at 0.50 per cent, all pods to the left of 0.50 per cent would be rejected as waste and those to the right would be the upgrade stream. Specifically, 1 496 kg would be removed, representing 12 per cent of the feed material. This would contain 6 per cent of the total copper feed and have an average grade of 0.39 per cent, while the upgraded stream would have an improved grade of 0.84 per cent copper, representing a recovery of 94 per cent of copper.

Figure 6 shows a similar histogram for the entire trial data set. In addition to the grade measurements from the MR analyser, the truck-by-truck grade estimates have been added.

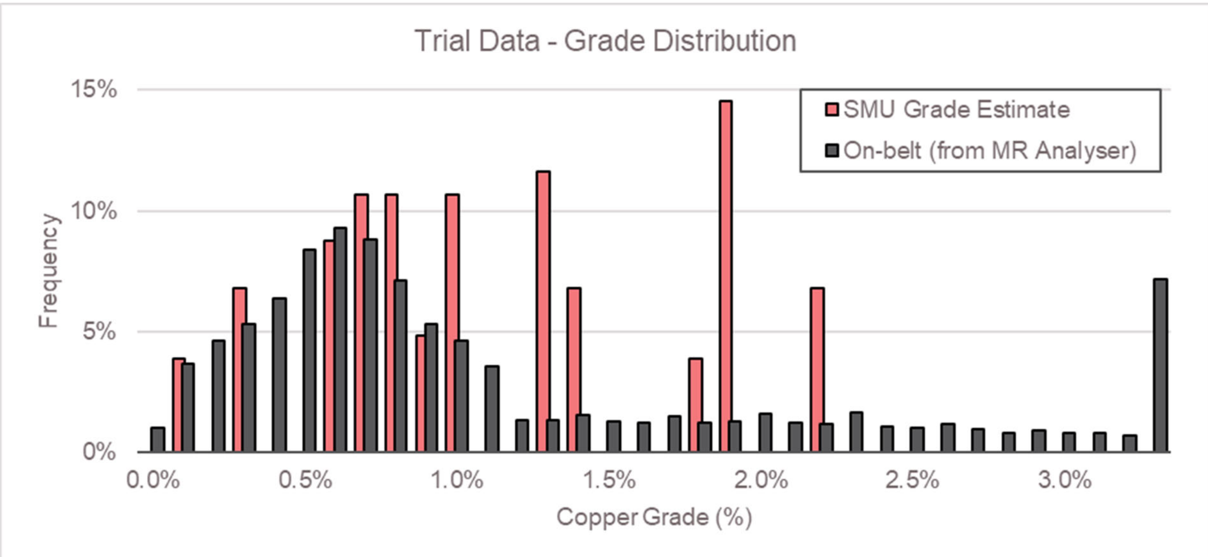

Figure 6 - Histogram showing distributions of grades assigned by site geologists (SMU Grade Estimate) and those generate by the MR analyser.

Calculating the weight retained and copper recovery over a continuous range of cut-off grades generates Figure 7, which allows a straightforward comparison of potential bulk ore sorting performance against truck assignment on SMU-grade estimates. In this chart, a result in the top left quadrant is desirable, as it indicates a higher proportion of metal recovered in the system within a smaller weight of material.

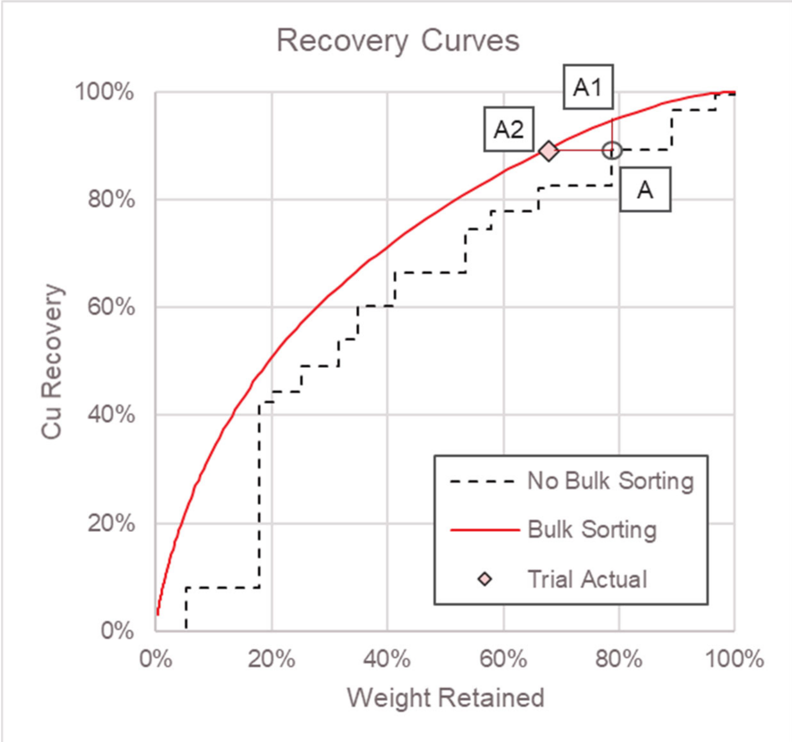

Figure 7 - Recovery curves comparing conventional geological truck contro (No bulk sorting)lvs bulk sorting.

Mark-ups in Figure 7 compare scenario “A” with a cut-off grade of 0.70 per cent copper applied on truck-by-truck grade estimates to two scenarios achievable using bulk ore sorting. Scenario “A1” applies a bulk ore sorting cut-off grade of 0.45 per cent, achieving a higher grade product and improved recovery for a fixed tonnage. Alternatively, scenario “A2” delivers equal recovery as scenario “A”, but in a lower quantity of upgraded material. Full data set shown in Table 3.

Table 3 - Full analysis for scenario comparison.

		A	A1	A2
		Not Sorted	Sorted	
Feed	Tonnes	1 413	1 413	1 413
	Grade	1.10%	1.10%	1.10%
	Cut-off	0.70%	0.45%	0.60%
Upgrade	Tonnes	1 111	1 122	932
	Grade	1.25%	1.31%	1.47%
Reject	Tonnes	302	291	481
	Grade	0.55%	0.27%	0.37%
Mining Recovery		89%	95%	89%
Grade Improvement		+0.15%	+0.21%	+0.38%
Weight Rejected		21%	21%	34%

The results of the trial show that bulk ore sorting can consistently achieve higher metal recovery in a lower proportion of process plant feed. This occurs both from removing sub-grade pods of ore from high grade material, but also by recovering good mineralised material from trucks otherwise designated as low grade or waste. In this case study, overall recovery improvement of between 6.3-7.8 per cent was demonstrated over conventional truck assignment, depending on the process feed tonnage desired.

There is the additional benefit of correcting misassignment of trucks for which the SMU grade varies significantly from actual measured grade, which is observed to occur frequently. Data comparing truck grade estimates to MR grade measurements are shown in Figure 8. Interestingly, across the full data population, the average grade based on SMU grade estimate is 1.13 per cent Cu, and compares quite closely to the average grade based on MR measurements, which is 1.10 per cent Cu. This close reconciliation demonstrates that such calculations carried out based on averages disguises the actual grade variability of deposits.

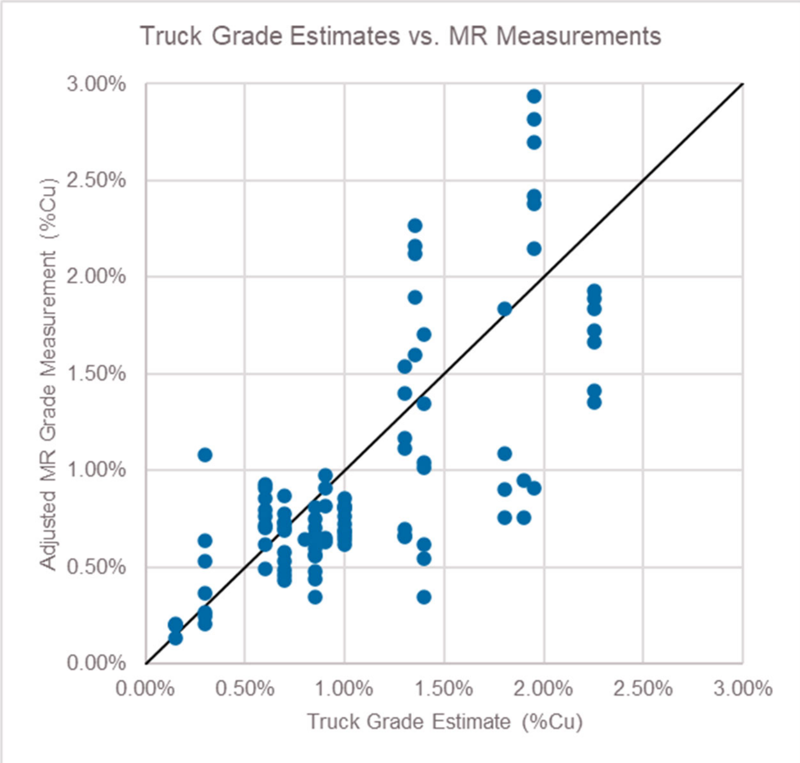

Figure 8 - Truck grade estimates vs. MR measurements

CONCLUSION

Bulk ore sorting is a relatively new technology to the mining sector. Many practitioners' understandings of the benefit derived from bulk ore sorting is confined to the objective of decreasing volumes and increasing metal grades for treatment downstream. This case study demonstrates that effective implementation of bulk ore sorting increases both process feed grade and total metal recovery.

Metal losses from bulk ore sorting are more than compensated for by improvements to mining recovery. In effect, bulk ore sorting is already being undertaken at every mine site through the process of truck assignment from truck grade estimates. Bulk ore sorting simply provides a cost-efficient system to improve the accuracy and granularity of grade estimates, and for an automated process to direct material. In this case study, a copper metal improvement of between 6.3-7.8 per cent is demonstrated against conventional truck assignment.

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APPENDIX A – PROVEN MINERAL APPLICABILITY OF MAGNETIC RESONANCE TECHNOLOGY

Mineral	Composition	Sensitivity
Chalcopyrite	$CuFeS_2$	High
Cubanite	$CuFe_2S_3$	High
Covellite	CuS	Medium
Chalcocite	Cu_2S	Medium
Enargite	Cu_3AsS_4	Low
Tennantite	$Cu_{12}As_4S_{13}$	Low
Cuprite+delafossites	Cu_2O + $CuFeO_2$	High
Tenorite	CuO	Low
Arsenopyrite	FeAsS	High
Orpiment	As_sS_3	High
Realgar	α-As_4S_4	High
Löllingite	$FeAs_2$	High
Niccolite	NiAs	Medium
Hematite	Fe_2O_3	High
Magnetite	Fe_3O_4	Very High
Maghemite	$Fe^{3+}{}_2O_3$	High
Pyrrhotite	$Fe^{2+}{}_{0.95}S$	High
Bismuthinite+others	Bi_2S_3	Medium
Stibnite+others	Sb_2S_3	High
Zircon	$ZrSiO_4$	Low
Cobaltite	CoAsS	High