Redefining the battery limits of processing plants – improving sustainability through the deployment of sensing technologies

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ABSTRACT

The role of separating ore from waste in an open pit mine is typically the realm of the production geologist who applies grade control to delineate ore from waste. The resolution of the grade control pattern is much coarser than the mining equipment used to recover and transport blasted ore to the mill or waste dump. This residual heterogeneity presents a unique prospect to initiate separation at the excavation front by means of real-time grade estimation for each shovel scoop. By doing so, shovel scoops or trucks below economic cut-off grade can be diverted to waste-dumps and similarly ore grade material can be directed from waste to the mill.

Once ore is introduced into the process, other sensing systems such as belt scanners are also useful tools in feed-forward control to the process plant. Presently, these innovations in online measurement are yet to become a standard piece of processing equipment, unlike their on-stream analyser counterparts which have gained widespread adoption.

At Red Chris, an X-ray florescence (XRF) based ShovelSense system has been successfully trialled and integrated into the fleet management system to take minerals processing to the mine face. In addition to the shovel mounted sensor, a Prompt Gamma Neutron Activation Analysis (PGNAA) based belt scanner has also been installed post crushing to measure additional ore properties ahead of the mill. This sensor allows the realisation of real-time geometallurgical model outcomes in the form of estimated ore hardness as well as forecasting tailing neutralisation potential.

INTRODUCTION

With the developments in sensor-based sorting techniques, the ability of operations to push the initial processing of material into the mine is becoming more prevalent. The mine-based assessment of material grade facilitates waste rejection as close as possible to the extraction process, maximising operational efficiencies by minimising dilution in mill feed and ore loss to the waste dumps. There are some dependencies however. *In situ* orebody heterogeneity is one requirement, while a sensor, or separation method, capable of detecting grade variability and the separation of ore from waste, is another.

At Red Chris, a process for the assessment of the potential for in-pit sorting combined with belt-based grade sensing was undertaken to determine the potential application of these methods. A theoretical heterogeneity assessment followed by bulk sorting trial using ShovelSense proved positive leading to the full-scale deployment of the technology. During this process, a Prompt Gamma Neutron Activation Analysis (PGNAA) sensor was installed on the conveyor between the primary crusher and the coarse ore stockpile (COS). The combination of these two techniques for the detailed characterisation of mined material has led to the operation's ability to ensure minimal misdirection of trucks. The belt sensor further confirms ShovelSense measured grades and adds detailed rock chemistry, offering the potential for feed forward control to the process plant.

RED CHRIS OPERATIONS

The Red Chris Mine is in the Golden Triangle of Northern British Columbia, approximately 80 km south of Dease Lake and 18 km south-east of the community of Iskut. Newcrest Mining Ltd, subsequently Newmont, became the operator of the Red Chris Mine on the 15 August 2019 after purchasing a 70 per cent stake of the operation from Imperial Metals (Stewart *et al,* 2021).

Geology

The Red Chris deposit is a significant copper-gold porphyry deposit located in British Columbia, Canada, and is economically significant due to its substantial copper and gold reserves. The highly deformed nature of the deposit reflects a history of volcanic activity, magmatic intrusions and hydrothermal alteration, resulting in the formation of valuable copper-gold mineralisation (Rees *et al*, 2015).

The mineralisation is associated with a series of faults and fractures that provided pathways for the movement of mineral rich fluids. This has led to the precipitation of thin wavy and thicker planar quartz veins containing chalcopyrite, bornite and magnetite. Dissemination of sulfide and gold mineralisation is also common locally around these vein structures. Gold predominantly occurs as microscopic inclusions in the copper sulfides, and occasionally as free grains in high-grade zones (Stewart *et al,* 2021). Material is classified in grade (or value) bins of HG (High Grade), MG (Medium Grade), LG (Low Grade), MW (Mineralised Waste), and Waste which is subclassified as NAG (Non Acid Generating) and PAG (Potentially Acid Generating).

Mining and processing

Ore is extracted from the Red Chris deposit using a conventional open pit mining method. Mining is performed by three large shovels: a Komatsu PC7000, P&H 2800 and a Hitachi EX3600, with support from three smaller excavators. The duty of ore and waste haulage is carried out by 18 trucks with a mix of Cat 793s and 785s.

Primary crushing of ore is done by a Metso gyratory crusher linked to a COS via a series of overland conveyors. The concentrator processes ore at a rate of approximately 10.5 Mt/a using a conventional semi-autogenous ball mill crusher (SABC) circuit with a target grind P_{80} of 150 μm. Throughput takes precedence over grind size, often resulting in typical grind P_{80} closer to 170–180 μm.

Rougher flotation is performed in two Eriez StackCells, six 200 m^3 and one 160 m^3 Outotec TankCells. The rougher concentrate is directed to the cleaners via a two-stage regrind circuit with a target P_{80} of 30 μm. The cleaner circuit configuration is variable with the flow sheet changing depending on operational requirements. Final concentrate with a grade of 23–24 per cent Cu is thickened and pressure filtered ahead of trucking to the Port of Stewart where it is loaded on a ship for delivery to the point of sale (Seaman *et al,* 2021).

The process plant produces non-acid generating (NAG) and potentially acid generating (PAG) tailings streams. The NAG tailings are further processed by semi mobile cyclones at the tailings dam, producing coarse sand for wall construction. This stream must have a sufficient ratio of neutralising carbonates and acid generating sulfides to achieve a neutralising potential ratio (NPR) of greater than 2 (Seaman *et al,* 2021).

The PAG tail is a pyrite rich product principally composed of cleaner-scavenger tailings and is required to be deposited sub-aqueously in the tailing's impoundment area.

OREBODY HETEROGENEITY AND SORTING METHODS

Heterogeneity of a mineral deposits refers to the natural variability in mineral distribution within the deposit. The variability can occur at various scales ranging from the microscopic, exploited by comminution and flotation circuits, to macroscopic differences seen vertically and horizontally within the deposit. The potential for sorting is dependent on the orebodies inherent heterogeneity with grade variability at the scale of the sorting instrument necessary for viability. Alongside this is the sensors capability to detect grade variability with sufficient accuracy and precision to enable confident decision-making using measurement outcomes (Moss, Klein and Nadolski, 2018; Nadolski *et al*, 2018).

Ore sorting, also known as preconcentration, refers to the practice of waste removal as early as possible in the mining system with the goal of increasing efficiency by minimising costs. Ore sorting process can broadly be broken down into two principal techniques: particle-based sorting and bulk ore sorting.

Particle based ore sorting

Particle based sorting refers to the use of systems that assess individual particles using a range of sensors to determine whether they are ore or waste. Typical sensors used by such systems are laser, RGB, X-ray transmission (XRT), X-ray florescence (XRF), electromagnetic, near-infrared (NIR) and Laser Induced Breakdown Spectroscopy (LIBS). This approach to ore sorting is best suited to low throughput operations processing high value commodities as the capital and operating cost are greater than bulk ore sorting techniques.

Bulk ore sorting

Bulk ore sorting, as the name suggests, is a technique used to assess bulk increments of material for determination or material type (Duffy *et al,* 2015). This approach can further be divided into belt-based sorting and in-pit sorting. Belt based ore sorting can employ the same sensors as particle-based sorting, with the addition of sensors like PGNAA, Gamma Activation Analysis (GAA) and Magnetic Resonance (MR). This approach characterises larger increments of material, typically 1–200 t, for the decision-making process and requires a diversion system to remove waste from the materials handling system.

A typical in-pit bulk ore sorting system can be either sensor based, using XRF or MR sensors, or can exploit the natural characteristics of the ore via mechanisms like screens to produce a waste and ore stream. In-pit sorting is deployed in the mine directly or at the pit crest via a truck-based grade measurement.

Belt based grade sensing using the Prompt Gamma Neutron Activation Analysis technology

PGNAA is a non-destructive analytical technique commonly used on conveyors for grade measurements of crushed ore. The technique uses a Californium 252 source located beneath the conveyor belt to generate neutrons that bombard the material on the moving conveyor. The neutrons interact with the ore on the belt and generate characteristic gamma rays that are registered by detectors mounted above the moving material. This generates a spectrum that is deconvoluted, allowing the elemental composition of the material to be determined (Noble, Thompson and Sanhueza, 2022; Noble, Strombotne and Gordon, 2024).

Newmont has been interested in the PGNAA technology for grade measurement of mined ore for several years. A system was initially installed at Cadia between the mine portal and the COS for the purposes of better understanding the PGNAA's potential in base metal operations and to generate an understanding of the nature of grade heterogeneity of ore in the Materials Handling System (MHS). This installation followed an early trial of a belt-based Magnetic Resonance (MR) sensor on the Ridgeway mine conveyor, later moved onto the Cadia MHS (Miljak, 2016). Cadia operates a block cave with material extracted from drawpoints across an extraction level. Drawpoint sampling indicated grade variability across the extraction level, suggesting that belt based bulk ore sorting may be possible. However, ore is drawn as evenly as possible from across the extraction level to ensure continued and gradual cave propagation, resulting in maximum ore recovery. This, however, leads to the homogenisation of the grade of the ore in the MHS leading to a stable plant feed grade but reducing the potential for belt-based sorting using the installed PGNAA sensor.

PGNAA sensors produce results at a frequency specified by the user. The measurement integration time is influenced by ore grade and a desired level of measurement precision. As part of the assessment of PGNAA usage in a base metal deposit, measurement integration time was evaluated to determine an acceptable level of precision for Cadia. This was done during a planned mine shutdown with an ore sample loaded onto the stationary belt within the sensor. Measurement time for the sample was then varied from 30 secs to 1 hr to generate sufficient data points for the assessment. A mean and a standard deviation were determined from the data to calculate a coefficient of variance as shown in Figure 1. From this analysis, a 2 min measurement integration time was selected as appropriate for Cadia as a reasonable compromise between precision and sampling frequency.

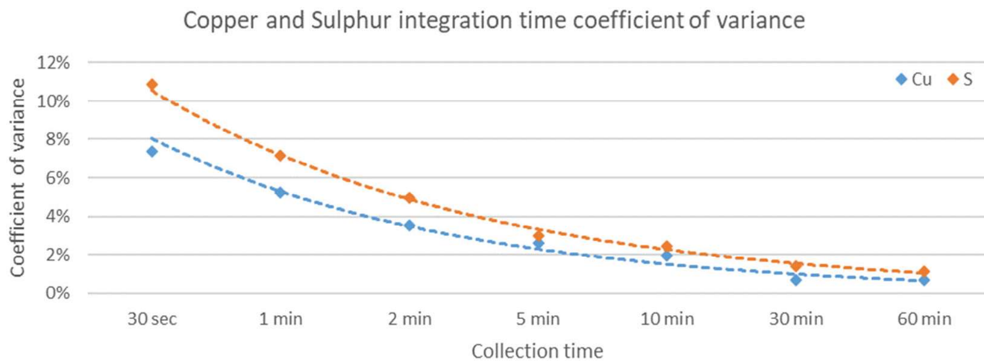

FIG 1 – Cadia PGNAA belt sensor measurement time coefficient of variance for copper and sulfur.

In early 2023, a CB Omni Fusion PGNAA belt sensor, supplied by Thermo Fisher, was installed and commissioned at Red Chris on the conveyor between the primary crusher and the COS. Important for a successful installation is the inclusion of an accurate weightometer proximal to the sensor. The sensor produces spectra that must be de-convoluted and converted into weight percent data. Necessary for this is an accurate input for tonnes in the selected measurement period.

The Thermo Fisher CB Omni Fusion PGNAA belt sensor utilises dual 40 µg Californium sources ensuring even grade data from the full cross-section of the ore on the belt. As with the sensor at Cadia, it measures a comprehensive suite of elements, including copper and sulfur. Analysis of the average daily grades produced by the belt sensor, the mill on-stream-analyser (OSA) for copper and cyclone overflow grab samples for sulfur show excellent agreement, as is seen in Figure 2. This confirms the findings from Cadia that this sensor type works well for base metal deposits.

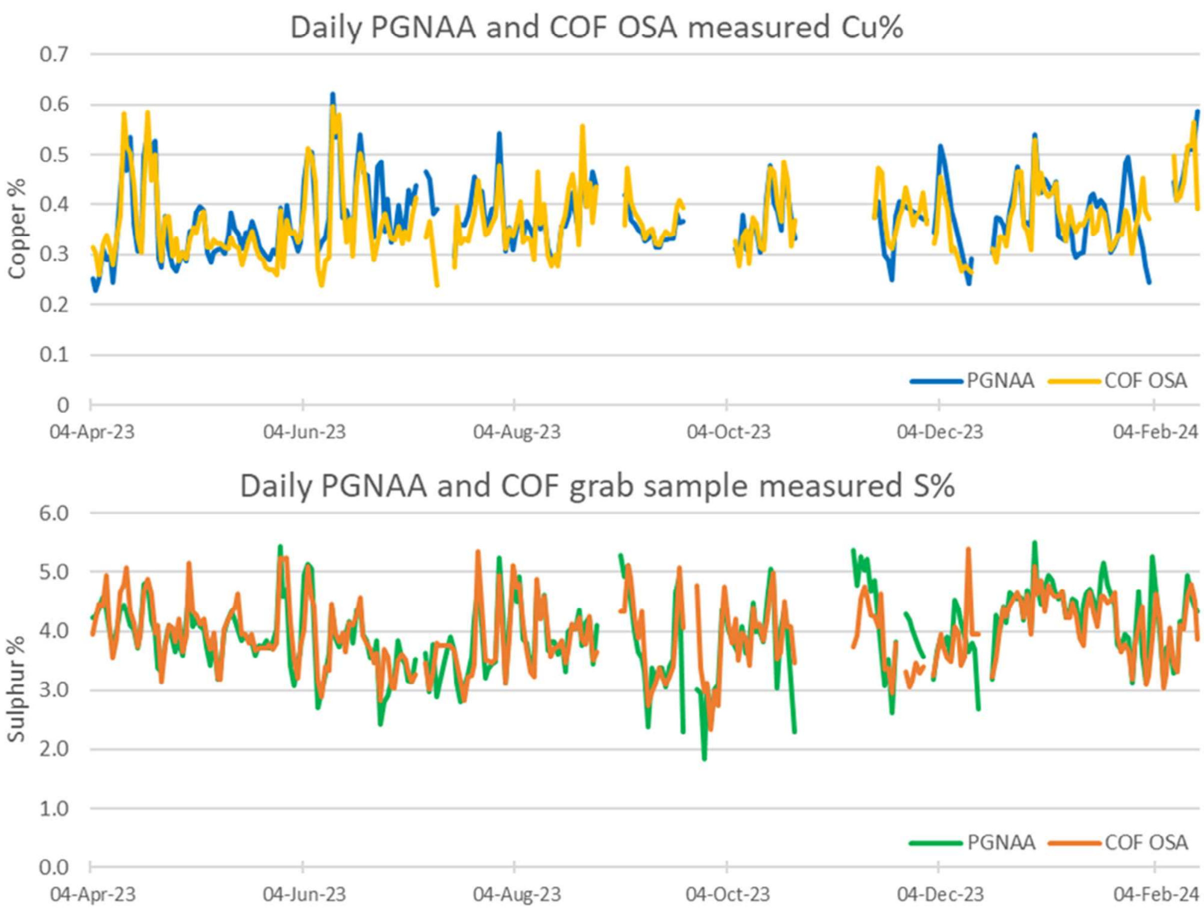

FIG 2 – Average daily copper and sulfur in mill feed as measured by the belt senor and the mill OSA for Cu grab samples.

ASSESSMENT OF BULK ORE SORTING POTENTIAL AT RED CHRIS

Proof-of-concept bulk ore sorting assessment for Red Chris

For the Red Chris deposit, a heterogeneity study was conducted at the University of British Columbia as part of a final year Capstone Project (Acacia *et al,* 2021). A 1 m drill hole assay composite data from across the deposit was provided for the analysis. This was composited to differing lengths to represent the heterogeneity present at the block model, grade control, truck and shovel bucket scale for an assessment of bulk ore sorting potential. Figure 3 graphically shows the four scales typically encountered by a mine.

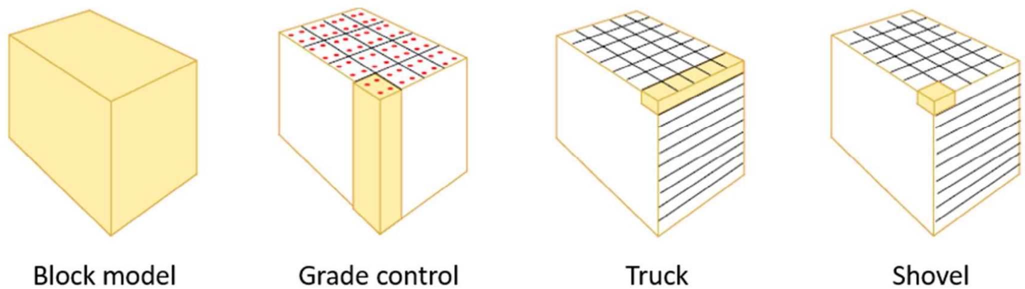

FIG 3 – Block model, grade control, truck and shovel bucket typically encountered by a mine, after Redwood (2018).

Re-combining of the assay data at different interval lengths provides an indication of the grade heterogeneity of the deposit (Acacia *et al,* 2021). For the analysis, interval lengths of 2 m and 4 m, representing shovel and truck scale heterogeneity, was compared to a 12 m composite representing grade control heterogeneity. The waste rejection potential from applying grade control on a per shovel scoop or per truck basis compared with the traditional grade control scale are presented in Table 1 for both the East Zone and Mian Zone pits at Red Chris. This provides a theoretical estimation of the *in situ* potential for bulk ore sorting at the shovel and truck scale for the Red Chris deposit.

TABLE 1

Heterogeneity analysis outcomes for bulk ore sorting at Red Chris.

	East zone		**Main zone**	
	Shovel (2 m)	**Truck (4 m)**	**Shovel (2 m)**	**Truck (4 m)**
Ore from waste	3.0%	2.5%	6.3%	6.2%
Waste from ore	13.5%	12.3%	14.0%	12.2%

SHOVELSENSE AT RED CHRIS

A decision was made to avoid belt based bulk ore sorting techniques to make use of the anticipated orebody heterogeneity as high frequency diversion systems and associated infrastructure are costly and take significant time to design and construct. This approach also sacrifices the waste to ore conversion as grade control defined waste material is not measured and therefore any contained ore is lost. Given that the heterogeneity analysis suggested that waste to ore conversions form a significant proportion of the total benefit, shovel or truck-based sorting techniques were deemed most appropriate.

An assessment of the available technologies that could be deployed at Red Chris to make use of the quantified orebody heterogeneity at the truck or shovel scale resulted in limited options. The gantry mounted magnetic resonance sensor from NextOre was not sufficiently advanced to be considered for deployment. The only commercially available technology deployable at the time was ShovelSense.

The ShovelSense technology is a grade measuring tool mounted in the bucket of a shovel. The system uses XRF to determine the copper grade of the mined material on a bucket-by-bucket basis, allowing a truck average grade to be determined. As material begins to fill the bucket, lasers in the heads detected a level change and activate the XRF emitters. Characteristic X-rays generated by the interaction of primary beam and rock mass are sensed by the detectors and converted to an elemental weight percentage. For Red Chris, this was deemed to be an appropriate technique and a decision was made to advance the project to a trial.

Bulk ore sorting trial using ShovelSense at Red Chris

The smallest shovel at Red Chris, the Hitachi EX3600, was selected for the initial trial with installation of a two head system occurring during a scheduled 72 hr preventative maintenance (PM) period. Fortunately, this shovel was scheduled for a bucket replacement during this PM, allowing the armoured sensor head to be welded into the replacement bucket prior to the PM.

Throughout the course of the trial, 1 092 528 t of material was measured via the extractions of 42 291 buckets of material, resulting in the filling of 5026 trucks. Of the 5026 trucks, 3485 were classified by grade control as ore and 1541 were waste. A high-level summary of ore movement as classified by grade control is shown in Table 2.

TABLE 2

High-level summary of ore movement during ShovelSense trial.

ShovelSense trial	# of trucks	Tonnes	Cu grade
Ore (classified by grade control)	3485	756 761	0.494
Waste (classified by grade control)	1541	335 767	0.120
Total	**5026**	**1 092 528**	**0.379**

Prior to the trial commencing, a general calibration was developed by testing ore samples in a laboratory setting and this was loaded onto the ShovelSense system. As the trial proceeded, a Red Chris specific calibration was developed with a focus on reconciliation at the ore/waste cut-off grade of 0.245 per cent copper. This revised calibration has proved reliable across the grade range and gives confidence that the system is on average, measuring the true copper grade of each shovel bucket with a comparison against grade control data showing excellent agreement as is seen in Figure 4.

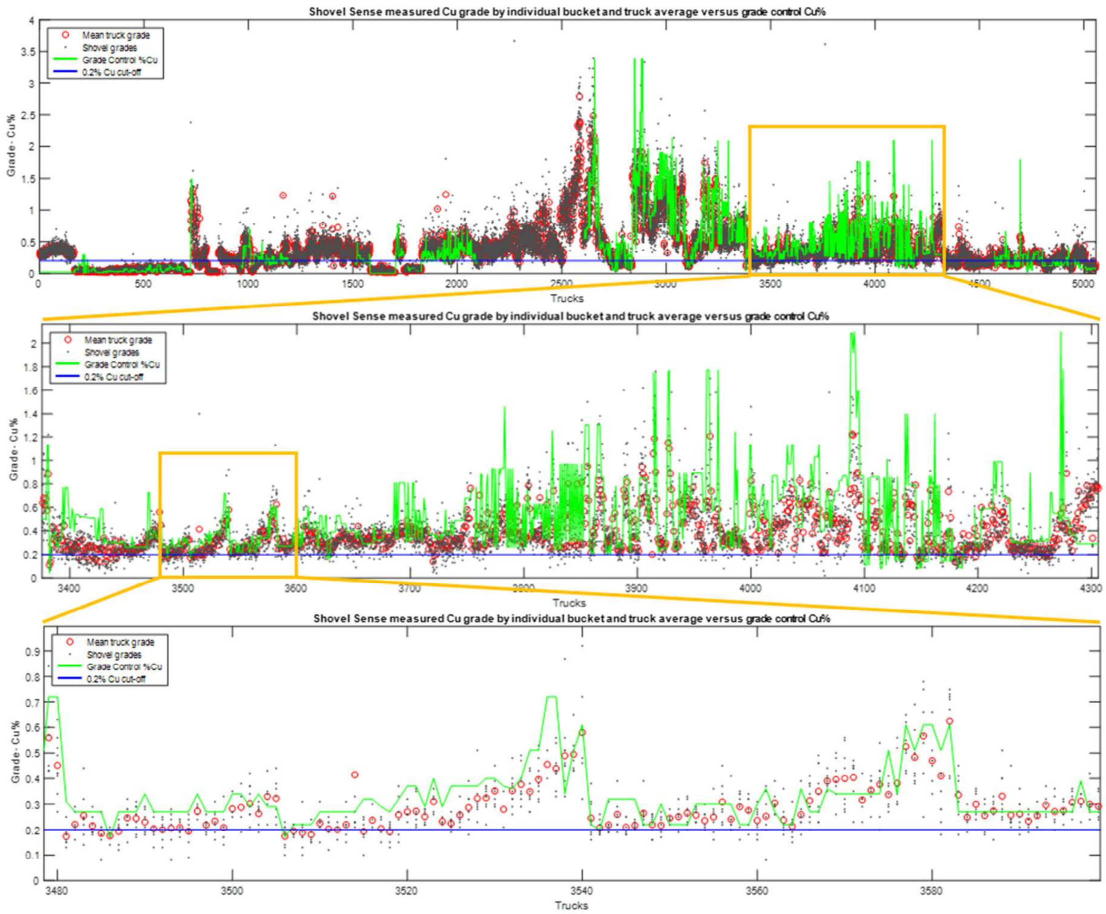

FIG 4 – ShovelSense measured copper grade by bucket and truck versus grade control predicted copper at three scales.

For ShovelSense, the potential for redirection is achieved by taking advantage of the finer resolution offered by the system. Each grade control assay characterises 800–1000 t of ore or waste and represents four to five truckloads of material. In contrast to this, each bucket that is mined with a ShovelSense equipped shovel produces a grade that is then averaged across the four to five buckets that make up the typical ~225 t load caried by a Cat 795 at Red Chris. This results in 16–25 times increase in measurement resolution and represents a significant step toward optimising grade delivery to the mill and the minimisation of metal loss to the waste dumps. Figure 5 graphically shows the resolution difference between individual bucket grades and grade control copper assays.

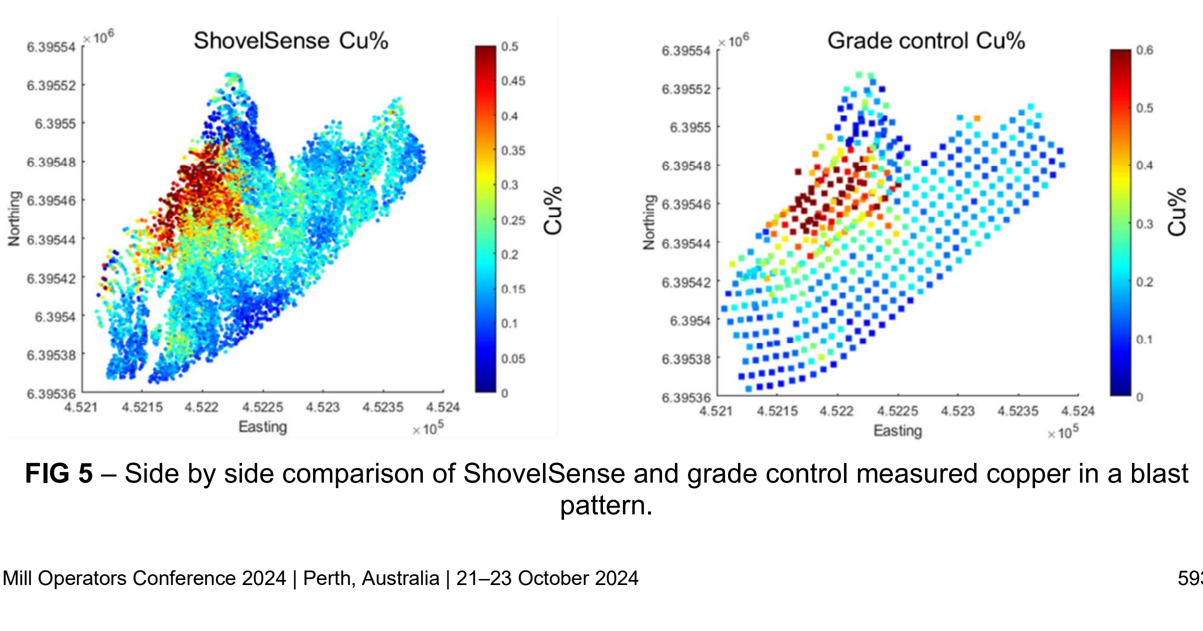

FIG 5 – Side by side comparison of ShovelSense and grade control measured copper in a blast pattern.

A spatial comparison of ShovelSense measured grades and blasthole defined dig polygons is shown in Figure 6. Misclassification is most apparent along ore/waste boundaries and within the low-grade dig blocks. This is partially due to the diffused nature of copper distribution in the deposit with a continuum existing between high-grade ore and waste. The designation of an ore/waste boundary in this continuum will inadvertently take in some waste in ore and ore in waste. Secondly, ore movement during blasting is not always accurately accounted for. This leads to some mixing along these boundaries resulting in misclassification.

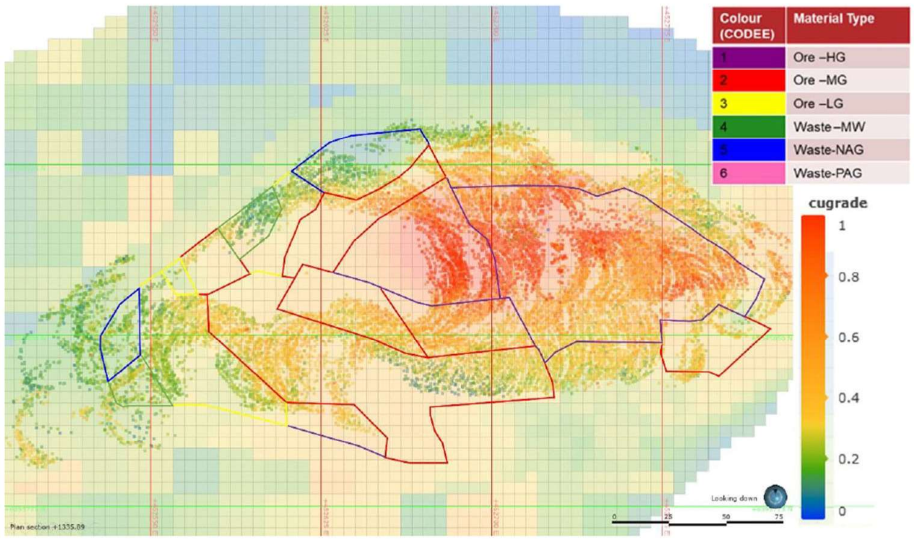

FIG 6 – Spatial comparison of ShovelSense and blasthole data overlayed with dig polygons.

Minimal misclassification is noted in the medium-grade dig blocks and almost none is apparent within the high-grade zones. This supports the pre-conceived belief that the true value of the system lies in bulk sorting material at the value margins of the deposit. Use of the system in homogenous high-grade, and to a slightly lesser extent, medium-grade zones will have a reduced benefit to Red Chris as the probability of diversion is less than when being used in low-grade ore or mineralised waste.

The ShovelSense trial showed that the grade control process is working correctly. ShovelSense measured grades correlated well with blasthole measured grade and the resulting dig blocks tightly bound the correct grade zones. The use of the ShovelSense system then is not to correct an existing problem but is to refine an already good grade control process.

Following successful completion of the trial, analysis of the data generated showed significant potential for re-claiming ore from waste and removing waste from mill feed. Figure 7 shows the potential for diversion from each of the major material classes with the low-grade and mineralised waste material types showing the greatest misclassification. This is expected as these material types straddle the ore waste boundary and any *in situ* grade heterogeneity has a greater likelihood of falling above or below the mine cut-off.

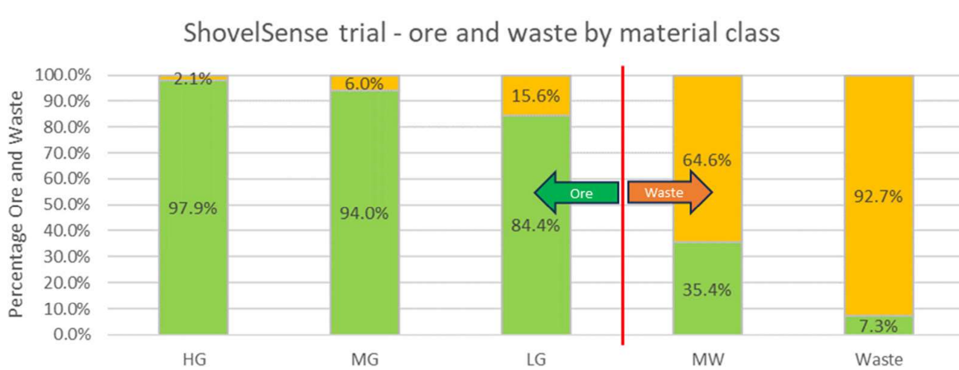

FIG 7 – Trial measured misclassification by material class.

For the duration of the trial, the system was recording data only, no connection back to dispatch was made to allow for truck diversions until the commercial deployment commenced. The reason for conducting the trial in this way was to ensure there was no impact on the current dispatch and control system until the value of the system had been confirmed.

Measured misclassification in each material type and resulting grade changes were overlayed across the existing mine plan, forming an understanding of potential for the operation. Based on this, commercial negotiations leading to the full-scale deployment were initiated with an agreement reached to install two systems on the large production shovels.

Commercial deployment of ShovelSense at Red Chris

The P&H 2800 (FS601) and the Komatsu PC7000 (FS620) were selected for commercial deployment as these two machines are the primary production shovels at Red Chris. ShovelSense was first installed on FS620, coming online on the 20th of March 2023 with FS601 following on the 28th of June 2023 (Figure 8).

FIG 8 – FS601 and FS620 at Red Chris currently using the ShovelSense system.

Both shovels use three XRF heads in the buckets to characterise the grade of material being mined. Figure 9 shows the armoured sensor heads in the shovel bucket. For the ShovelSense systems in use at Red Chris, copper is the only element currently being reported. Secondary elements of Fe, Mo, Zn, Sr and As are being tracked with the hope they can be used for discriminating other ore characteristics that can drive system performance in the future.

FIG 9 – Three head system on the shovels at Red Chris showing the outer armour and the inner laser, XRF emitter and X-ray receiver.

ShovelSense deployment outcomes

From installation to May 2024, ShovelSense equipped shovels have moved 11.3 Mt of material in ~51 000 trucks. Of the 11.3 Mt mined, 2.4 Mt of material has been redirected representing 21.6 per cent of all material mined using the ShovelSense systems:

- 1612 kt of ore has been re-directed from waste and at an average grade of 0.30 per cent Cu and 0.20 g/t Au. This material has a Net Smelter Return (NSR) of $24.58 and is classified as low-grade ore.
- 825 kt of waste has been removed from ore at an average grade of 0.17 per cent Cu and 0.13 g/t Au. This material has an NSR of $13.59 and is classified as waste.
- This has resulted in a 787 kt increase in ore available for processing at an average grade of 0.42 per cent Cu and 0.27 g/t Au and is on average classified as medium grade ore (Table 3).

TABLE 3

High-level summary of benefit derived by using the ShovelSense system.

ShovelSense benefit summary	Tonnes	Cu%	Au g/t	NSR	Material class
Diverted tonnes – waste to ore	1 612 300	0.30%	0.20	24.58	1 612 300
Diverted tonnes – ore to waste	825 294	0.17%	0.13	13.59	825 294
Net change in ore	**787 006**	**0.42%**	**0.27**	**36.21**	**787 006**

The generation of an additional ~787 kt of ore represents an 18.1 per cent increase in ore produced by the mine via the conversion of above cut-off grade waste material. When viewed as a strip ratio, the change is significant with the waste to ore ratio changing from 1.59 t of waste per tonne or ore to 1.19 t of waste per tonne of ore.

The percentage of misclassification since deployment (Figure 10) in each material class has exceeded that expected from the initial trial (Figure 7) with all material types showing an increase in the number of re-directable trucks. Of note is the MW where 50 per cent of all mined material is ore and the residual material now a true waste.

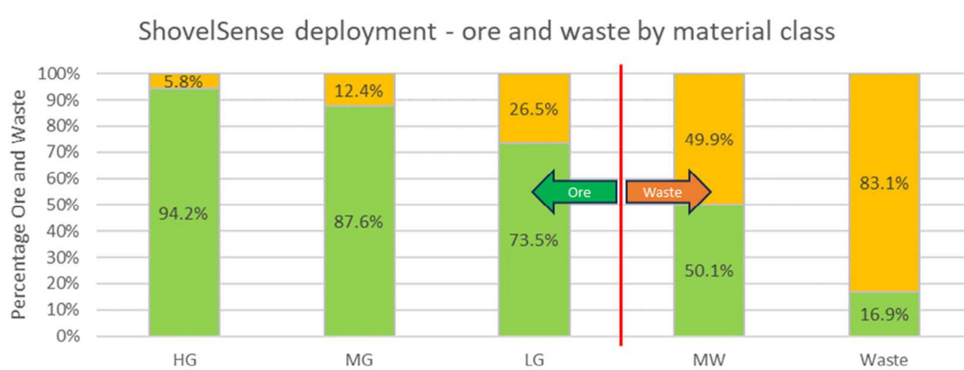

FIG 10 – Measured misclassification as characterised by ShovelSense during commercial deployment.

From installation to May 2024, 67 blast patterns across seven benches have been mined using the ShovelSense systems. Some of these patterns had very little material diverted while others had a significant percentage of the total blast redirected. Redirections occur in patterns where ShovelSense measured copper grades deviates from the grade control marked up grades. This can be due to mixing during basting or conservative standoffs used along ore waste boundaries to minimise dilution in plant feed.

One example of this occurred on bench 1376 with blast 33. ShovelSense was used to mine ~256 kt of material from this blast that was principally designated as PAG and mineralised waste. During mining of the location, ~155 kt of ore was reclaimed from waste via the redirection of 680 trucks. ~96 kt, or 62 per cent, of the redirected ~155 kt of material was classified as medium grade by ShovelSense. Table 4 shows the re-directed material tonnes due to ShovelSense and Figure 11 shows the grade control markup, ShovelSense measured Cu% and re-classified material in pattern 1376–33.

TABLE 4

Re-classified material from blast pattern 1376–33.

Pattern 1376–033	Grade control (t)	ShovelSense (t)	Change (t)
HG	0	459	459
MG	0	95 943	95 943
LG	27 631	85 712	58 081
MW	107 810	38 167	-69 643
Waste	120 104	35 265	-84 839
Total	**255 544**	**255 544**	**0**

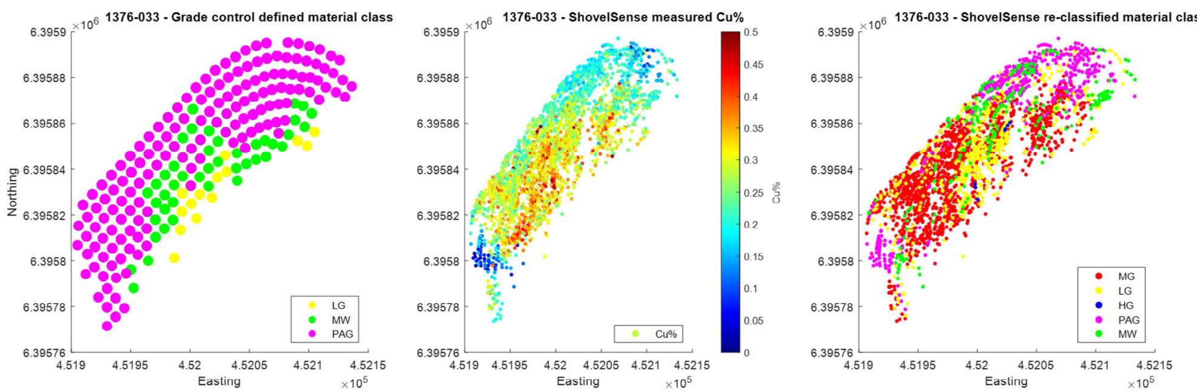

FIG 11 – Grade control markup, ShovelSense measured Cu% and re-classified material in pattern 1376–33.

A comparison of the percentage of misclassified material from the proof-of-concept assessment using downhole drill core assays data and the current commercial deployment shows a significant increase in actual redirections. The heterogeneity analysis assessed only vertical *in situ* orebody heterogeneity due to the constraints of the supplied data. This does not account for mixing during blasting or for conservative standoffs used along ore waste boundaries. As a result, actual waste from ore and ore from waste re-directions are higher than the theoretical assessment. This has ultimately led to a greater than anticipated number of truck re-directions, resulting in ShovelSense producing more than the predicted benefit for Red Chris. Figure 12 graphically illustrates the difference in the percentage of ore in each material class. Of note is the mineralised waste and waste classes that both show an increase in their total ore content by ~15 per cent each.

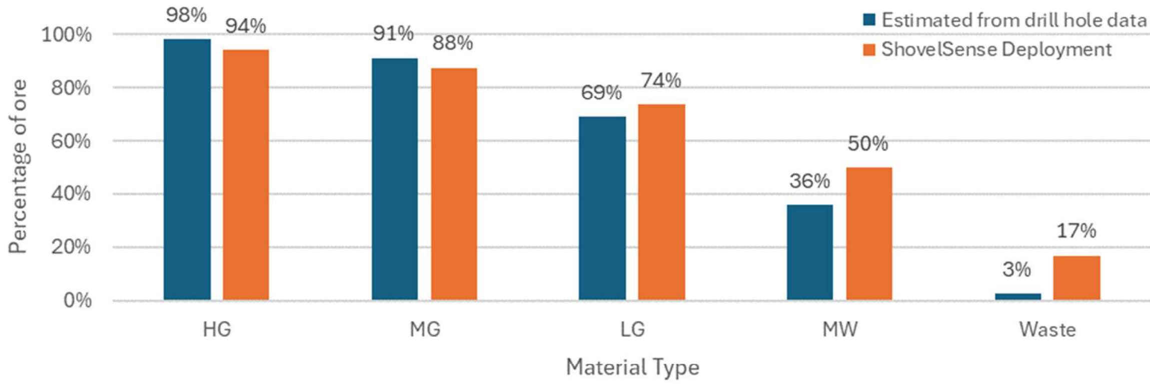

FIG 12 – comparison of the theoretical and actual ore content in individual material classes.

Validation of ShovelSense outputs

Verification of ShovelSense measured copper grades is important in developing trust in the outputs of the system. Poor measurement accuracy or low precision will result in the incorrect diversion of trucks and an erosion of value for Red Chris. For Red Chris, three methods for the validation of ShovelSense outputs were considered.

Validation against grade control assays

Initial checks against in-pit grade control assay, used to define ore dig blocks, were undertaken to verify ShovelSense outputs. ShovelSense bucket grades are averaged to individual trucks and assessed against grade control expected grades for the dig areas. Agreement between these two data sources was good with the expected variability present driving redirections. Figure 13 shows a line plot of the two data sets from 1–30 November 2023 for demonstration of conformity of grade results.

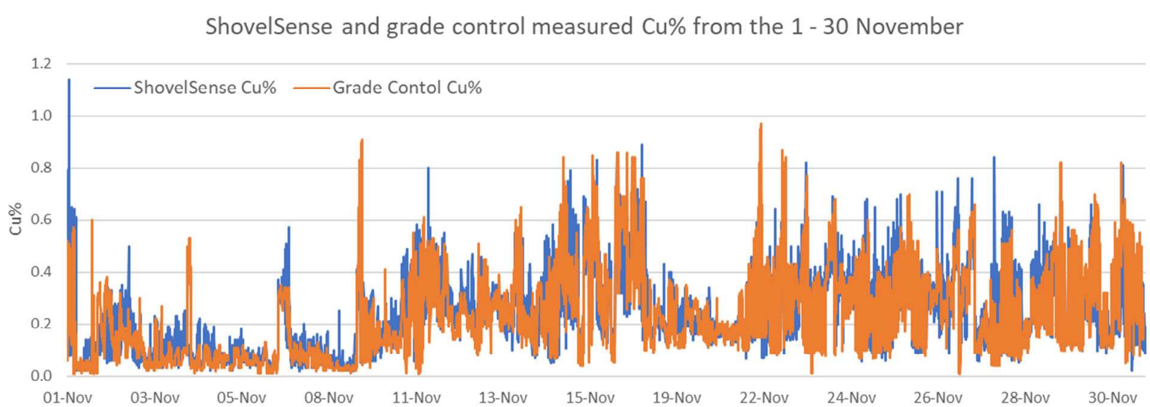

FIG 13 – ShovelSense and grade control measured Cu%.

Validation against belt sensor and mill OSA grades

Red Chris has two other independent measurement methods used to characterise the grade of the material being delivered to the mill from the pit. The first of these is the above mentioned PGNAA belt sensor located between the primary crusher and the COS.

The second meaurement point is the OSA measuring a range of elements in streams within the process plant including copper. The OSA is periodically calibrated and is checked against shift composites every day. Rock drawn in from the COS is milled in the grinding circuit and then directed to flotation via the primary cyclones. A measurement of the primary cyclone overflow is made by the OSA and represents feed to the flotation circuit. This material should, in a broad sense, have a similar grade to the rock delivered to the COS. Difference will be noted as there is mixing in the COS and SAG mill with the re-circulating load in the ball mill further homogenising short-term grade variability.

For a comparison of these three independent data sets, only trucks filled using ShovelSense equipped shovels directed to the primary crusher were used. To compare ShovelSense grades against the belt sensor and OSA grades, time offsets were used to account for travel time on the belt and estimated residence time in the COS and grinding circuits. Table 5 defines the offsets used.

TABLE 5

Time offsets for ShovelSense, belt sensor and mill OSA grade alignment.

Time offsets for grade alignment	Minutes
Primary crusher to belt sensor	5.8
Belt sensor to COS	8.6
COS residence time	216
Grinding circuit residence time	6.5

ShovelSense, the PGNAA belt sensor and OSA measured copper grades show excellent argeement, providing further confidence in ShovelSense outputs. Figure 14 shows the grade data for the three data sets from 1 July – 30 September 2023.

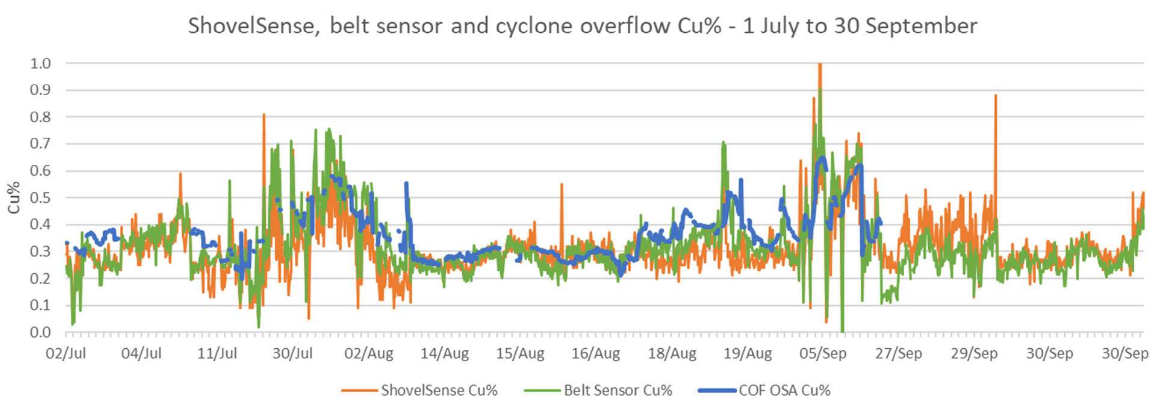

FIG 14 – ShovelSense, belt sensor and OSA measured copper grades.

Bulk sample verification of ShovelSense measured copper grades

To generate an additional layer of certainty on the grades being produced by ShovelSense, a bulk re-direct stockpile of ore reclaimed from waste was generated for batching through the belt sensor and mill to confirm the grade alignment. From 1–21 September 2023, ~48 kt of ShovelSense re-directed material from waste to ore was produced and stockpiled at an average measured grade of 0.25 per cent Cu.

The re-directed material was processed through the primary crusher in two campaigns. The first campaign involved 19 362 t of material fed between September 25th and 26th, following an extended crusher and mill shutdown. A mean grade of 0.28 per cent Cu was measured at by the PGNAA belt sensor while a composite of grab samples from the cyclone overflow produced a grade of 0.27 per cent Cu.

The second campaign processed 28 579 t of material, depleting the re-direct stockpile and completing the trial. For this second campaign, a mean grade of 0.27 per cent Cu was measured by the PGNAA belt sensor. The OSA for was offline during this period and no measurement of copper in cyclone overflow was available for comparison.

The overall average grade of the two campaigns was consistent at 0.27 per cent Cu and was supported by the cyclone overflow assay during the first campaign. These results were comparable to the ShovelSense stockpile average grade of 0.25 per cent Cu indicating that the system is successful in characterising the copper grade of mined material.

The grade validation steps used to determine ShovelSense's ability to discriminate between near cut-off ore and waste provided confidence in the continued use of the system and confirmed the belief that its continued use represents an important value contribution to production at Red Chris.

Fleet management integration

For the productive use of the ShovelSense system, some form of integration with dispatch and the fleet management system (FMS) is needed to facilitate truck diversion. At the time of installation, Red Chris used MineStar version 5.5 as their FMS and this had no ability to accept inputs from the ShovelSense system for truck diversion.

As a result, a third-party interface, MineMage, was used to access ShovelSense bucket data and MineStar truck routing data to produce a truck based average grade and assigned dump destination. When there was a mismatch between grade control assigned material class and ShovelSense characterised material class, a notification was provided to dispatch to reroute the truck. An example of the interface is shown in Figure 15, showing three trucks that need to be redirected from waste to ore.

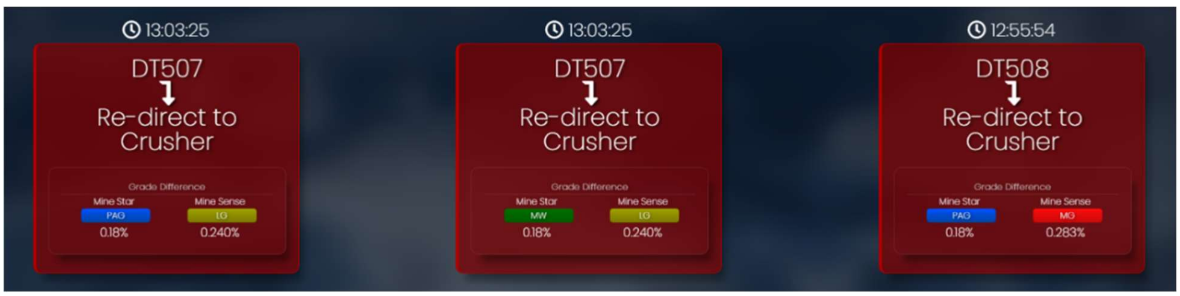

FIG 15 – MineMage truck redirection interface.

This method, while functional, requires attention from dispatch and is suboptimal. On occasion, truck redirections are missed, or they are incorrectly redirected due to other operational pressures that cannot be ignored. Full integration with the MineStar FMS for seamless redirection is needed as this will ensure all redirections are captured.

An upgrade of MineStar from version 5.5 to version 5.8 provided a mechanism for the integration of the two systems. Minestar Version 5.8 contains a ShovelSense add-in that can take in bucket grade data during loading to produce a truck average grade. Truck average grades are compared to a rule table and a material class assigned. If there is a mismatch between the originally assigned material class and the newly assigned material class, an auto redirection notification is sent to the truck. This method reduces the effort required by dispatch and maximise redirections.

Conversion to NSR based diversions

Material classification at Red Chris is defined using a calculated Net Smelter Return (NSR) with Cu and Au grades driving the outcome. NSR is the net revenue that Newmont receives from the sale of the copper and gold products produced by the operation less site costs and transportation and refining costs. The NSR calculation includes plant recovery in the equation with recovery being variable and dependant on both copper and gold head grade.

As ShovelSense is only measuring Cu in each bucket mined, material classification is linked to the mined Cu grade. A general relationship between copper and gold grade was established using grade control data to assist with material type classification. From this, a copper grade of 0.245 per cent Cu was established as the dividing point between waste and ore as at this copper grade, an average gold grade of 0.19 g/t will produce enough value that the material is classified as ore.

As a result of this, there will be occasions when material that has been classified as either ore or waste by grade control using both copper and gold grades, could be reclassified by ShovelSense due to the absence of a gold grade. To rectify this, gold grades, as measured by grade control, in the local vicinity of the shovel, are drawn into the material type classification so that an NSR for each shovel bucket, and then truck, can be calculated to better define material class. This aligns ShovelSense material classification with grade control material classification, reducing incorrect diversions due to incorrect material classification.

System reliability

Initial availability of the ShovelSense system was low, principally due to XRF head failure. Discussions with MineSense revealed a change in supplier of one of the components in the heads that was prematurely failing. This problem has now been mostly resolved with head failure significantly less than it was in the past. Current run hours on the heads have significantly improved with most heads now reaching or exceeding the expected 800 hrs of operational time. The current head 3 on FS620 has operated for over 2000 hrs.

For FS620, recent reliability issues are the result of damage to the main extension cable and the signal processing unit (SPU). The SPU is not located in a standard position for the system due to interference with the hydraulic lines to the bucket. FS620 is a Komatsu PC7000 shovel and one of only two in the world. The bucket, stick and hydraulic line routing is not common to any of the other Komatsu shovels and SPU placement during system installation caused some delays as a result of the fouling. Eventually the SPU was installed high on the outside of the bucket exposing the main cable to rock strikes during operation. This has caused some system downtime, however, cable replacement can be completed in a shift change.

Additional downtime for the system has been incurred as previously no maintenance on the ShovelSense systems was done outside of schedule PM windows. This has at times led to many unnecessary days of downtime for a relatively minor repair that could have brought the system back online and productively contribute to the success of Red Chris.

As an example, the system on FS620 was down for 11 days from 6–16 September 2023, due to extension cable and SPU damage. These issues were addressed in the PM from 14–16 September 2023, but could have been resolved earlier over one or more shift changes.

ShovelSense availability has been improving from September onwards with ShovelSense availability on FS601 exceeding that of the shovel. FS620 availability is also improving with 100 per cent availability in the month of November. Figure 16 shows the days in service for the two shovels and the corresponding ShovelSense systems.

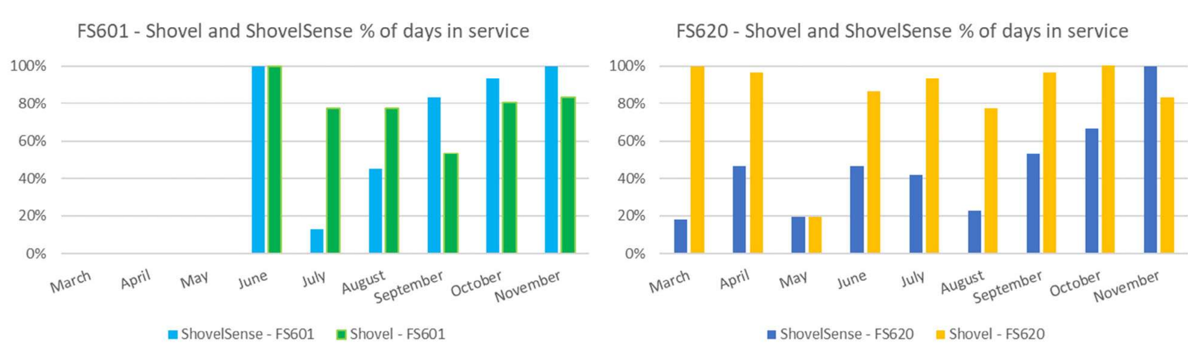

FIG 16 – Shovel and ShovelSense percentage of days in service.

PGNAA USAGE

Opportunities for greater integration of PGNAA outputs in plant operation

Full utilisation of the belt sensor as an input to the process control system is a work in progress. At present, copper and sulfur grades in feed to mill are monitored with intentions to begin to use these as inputs into the Met Accounting process. Additionally, sulfur grades in mill feed can be used as an input to reagent dosing for the flotation circuits.

NPR of the circuit tailings is an important criterion that needs monitoring as a measured value greater than two is required to avoid the requirement for sub-aqueous tailings deposition. The belt sensor is capable of measuring calcium, principally hosted in neutralising carbonates, and acid generating sulfur in plant feed. Using this data, a quick estimation of NPR in plant tailings can be generated. This will in turn minimise the need for sub-aqueous deposition and greater use of the rougher scavenging circuit for copper recovery rather than pyrite recovery as a PAG tailing stream.

A relationship using rock chemistry, measurable by the belt sensor, and Bond Work Index is being developed. This, when used in conjunction with recently installed SAG mill feed particle size cameras, will assist with isolating ore driven process deviations from operational upsets. When linked with pit location via ShovelSense, some forewarning of future process outcomes may be possible helping to continually maximise recovery.

CONCLUSIONS

Within the Red Chris deposit, there is significant *in situ* orebody heterogeneity at a scale much finer than that defined by grade control. Differences between truck scale and grade control scale heterogeneity allow for a waste rejection stage and additional ore recovery from waste between the mine and the mill. Estimation of heterogeneity conducted on downhole drill assay data was confirmed with actual measurements, and later truck diversions, providing confidence that a method for predicting bulk ore sorting potential from available *in situ* information is both feasible and realistic.

To date, ShovelSense has been responsible for the generation of an additional ~787 kt of ore, representing an 18.1 per cent increase in ore produced by the mine via the conversion of above cut-off grade waste material. When viewed as a strip ratio, the change is significant with the waste to ore ratio changing from 1.59 t of waste per tonne or ore to 1.19 t of waste per tonne of ore.

A combination of sensors has proven to be effective at measuring grades near cut-off to pre-process ore ahead of the mill with the potential for adaption to different mining techniques in development with field trials currently underway.

The use of multiple sensing system within an operation allows for ongoing cross-validation of measurements. This can then be used to detect individual system calibration drift and enhances operation wide grade data measurement confidence.

Belt sensing precision and measurement frequency can be fine-tuned depending on the application and the accepted measurement error by the end user.

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