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Bulk Ore Sorting Using Magnetic Resonance Sensing: Kansanshi Mine Case Study

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ABSTRACT: Grade is critical to profitability in a mining operation but it is a naturally occurring characteristic that is beyond the control of the miner. As global grades decline, and new high-grade discoveries become increasingly rare, operating mines and development projects are facing mounting pressure to materially improve the efficiency of mining systems.

Any resolution to this problem needs to deliver a combination of improved revenue and decreased cost without introducing excessive complexity, and all while maintaining or improving upon the social and environmental performance of the mine and its owner. Where applied properly, bulk ore sorting systems represent an opportunity for miners to simultaneously achieve these outcomes.

This paper presents a case study of successful bulk ore sorting (BOS) trial at the Kansanshi mine. BOS effectiveness was confirmed and validated at a rate of 2,800 tonnes per hour, with measurements of mineralogical grade provided at intervals of 4 seconds corresponding to 3.1 tonne pods using a magnetic resonance analyser (MRA). The primary findings of this case study are 1) validation that the MRA technology functions as claimed and is well suited to chalcopyrite dominant copper sulphide orebodies; 2) validation of the fundamental theory of bulk ore sorting, that bulk heterogeneity in ore persists after the primary crusher and effective bulk separation can effectively preconcentrate ore at significant tonnages; 3) quantification of BOS results for the given orebody; 4) provision of technical details for retrofitting of BOS to an operating mine; and 5) description of a new validation methodology that is believed to be genuinely novel and successful.

INTRODUCTION

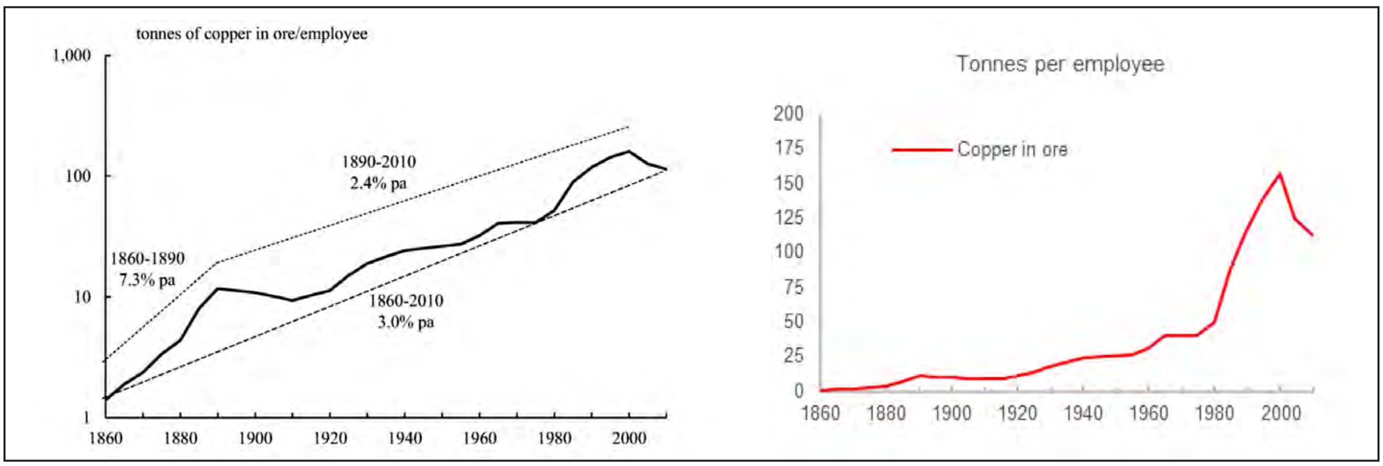
Background

Sensor based bulk ore sorting is an emerging technology with potential to deliver a step-change in environmental impact and metal extraction economics to the mining industry. Bulk ore sorting seeks to provide a capital efficient mechanism, capable of handling throughputs of the world's largest mines, to preconcentrate ore by autonomously interrogating the grade of mined material and separating that which is high value from that which is low.

Mining productivity has begun to decline in recent years. The mechanisation of the mining industry throughout the 20th century delivered significant improvements to the productivity of both labour and capital in producing the metals necessary to drive modern life. However, these gains in productivity were often the result of economies of scale where selectivity was sacrificed for disproportionate gains in efficiency. Modern mining has optimised these economies of scale, with ultra-class mining trucks matched to the very large electric shovels, mining is relatively indiscriminate as an extraction methodology. In spite of that, as shown in Figure 1, evidence suggests that cost and labour efficiencies peaked around the year 2000 and are now in reverse. The natural procession of declining grades is now eroding productivity gains more quickly than technological advancements have been able to overcome.

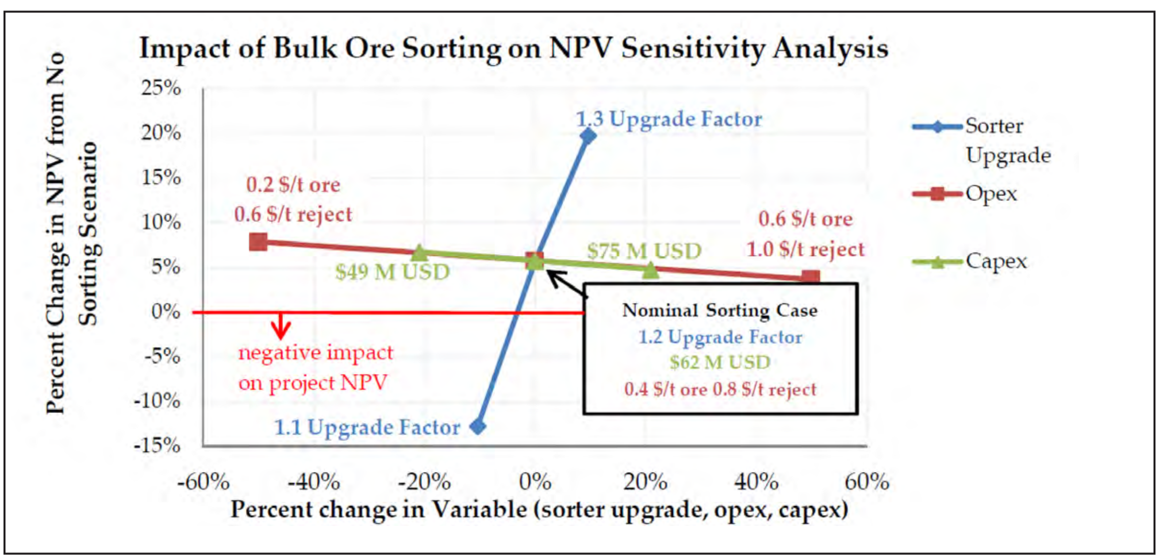
A body of literature has been developed over a number of years reviewing potential options for application of bulk ore sorting and calculating the scale of impact. These assessments have shown that improvements delivered by bulk ore sorting have the potential to drastically improve the value of operations. An example output from one such study is shown in Figure 2, which shows the potential to improve NPV of a project by as much as 20% by preconcentrating ore.

These studies have been effective at showing how dramatic the results of effective BOS can be, but relatively little



Source: Humphreys, 2020

Figure 1. Productivity growth in US copper ore mining in log scale (left) and the same data in linear scale (right)



Source: Duffy, Valery, Jankovic, Holtham, & Valle, 2015

Figure 2. Sensitivity analysis of the impact of ore sorting on NPV

published material exists for case studies where technologies have been trialled and proven in the field.

Purpose

The purpose of this paper is to provide technical details for a case study of successful BOS implementation undertaken at the Kansanshi Mine, starting in 2020. This case is understood to be the highest throughput implementation of sensor based bulk ore sorting publicly reported to date.

The paper will describe:

- BOS system design, including:
  - Selection and placement of equipment;
  - Sensing technology; and
  - Installation, commissioning, and operations.
- Verification methods; and
- Sorting separation results

Kansanshi Mine

The Kansanshi mine (100% First Quantum Minerals "FQM") is located in the North-Western Province of Zambia. Kansanshi has an extended history of operation, with the modern mine being established by FQM in the early 2000s.

Mining

Mining at Kansanshi is by conventional open pit mining using shovel and truck mining techniques. Ore types, corresponding to independent processing streams in the Kansanshi mineral processing plant, are categorized as sulphide, oxide and mixed. The metallurgical processing system is designed to operate with a high degree of flexibility to suit the various ore types received. As a result, there are three main processing routes, with independent dump stations and crushers, which feed corresponding processing circuits. The flexible design of the process plant allows ores to be treated through any of the three circuits which allows balancing of tonnages as each circuit has different capacities.

Geology and Mineralogy

Copper mineralisation at Kansanshi occurs as three deposits (Main, North West and South East). The deposits are located within domal structures along the crest of a regional antiform. Deposit mineralisation is closely associated with these domes.

Three styles of primary sulphide mineralisation are associated with these deposits:

- disseminated stratabound mineralisation
- sub-vertically dipping, quartz-carbonate-sulphide veins crosscutting the stratigraphy
- localised breccia mineralisation

Weathering influences mineralisation as follows:

- near surface weathering in the saprolitic zone
- around vertical veins, with oxide copper mineralisation predominantly evident as malachite, tenorite and chrysocolla
- mixed primary and secondary sulphide copper mineral assemblages in transitional zones between weathering zones
- pervasive shallow to deep weathering located along geological structures

Primary sulphide copper mineralisation is mostly chalcopyrite, with minor bornite. Oxide mineralisation is mostly chrysocolla with malachite. The transition zone contains mixed oxide, primary sulphide, secondary chalcocite and minor native copper and tenorite. Minor copper is hosted in clay and mica minerals, and is classified as refractory. Gold is associated with copper mineralisation.

(Gray, Lawlor, & Briggs, 2020)

BULK SORTING EQUIPMENT CONFIGURATION

In 2019, Kansanshi Mineral Processing and First Quantum Minerals corporate personnel began discussion for the use of sensor-based BOS using an MRA to address the mineralogical complexity associated with the primary sulphide ore. Shown in Figure 3, The BOS equipment would be retrofitted to the existing primary sulphide crushing circuit, comprising of primary gyratory crusher and secondary cone crusher feeding to the coarse ore feed stockpile for the sulphide circuit, along with associated feeders, conveyors, and transfer chutes. The BOS equipment to be retrofitted would include:

- MRA configured for chalcopyrite grade measurement, and
- Reject conveyor belt discharging to stockpile.

Modifications of existing equipment would include:

- Addition of hydraulically actuated rock box diverter to a chute.

Retrofitting to Existing Crushing Circuit

The existing layout of the KMP primary sulphide crushing circuit presented a favourable opportunity for retrofitting of BOS system. CV-1201 receives primary crushed ore from a gyratory crusher and discharges to a tower fitted

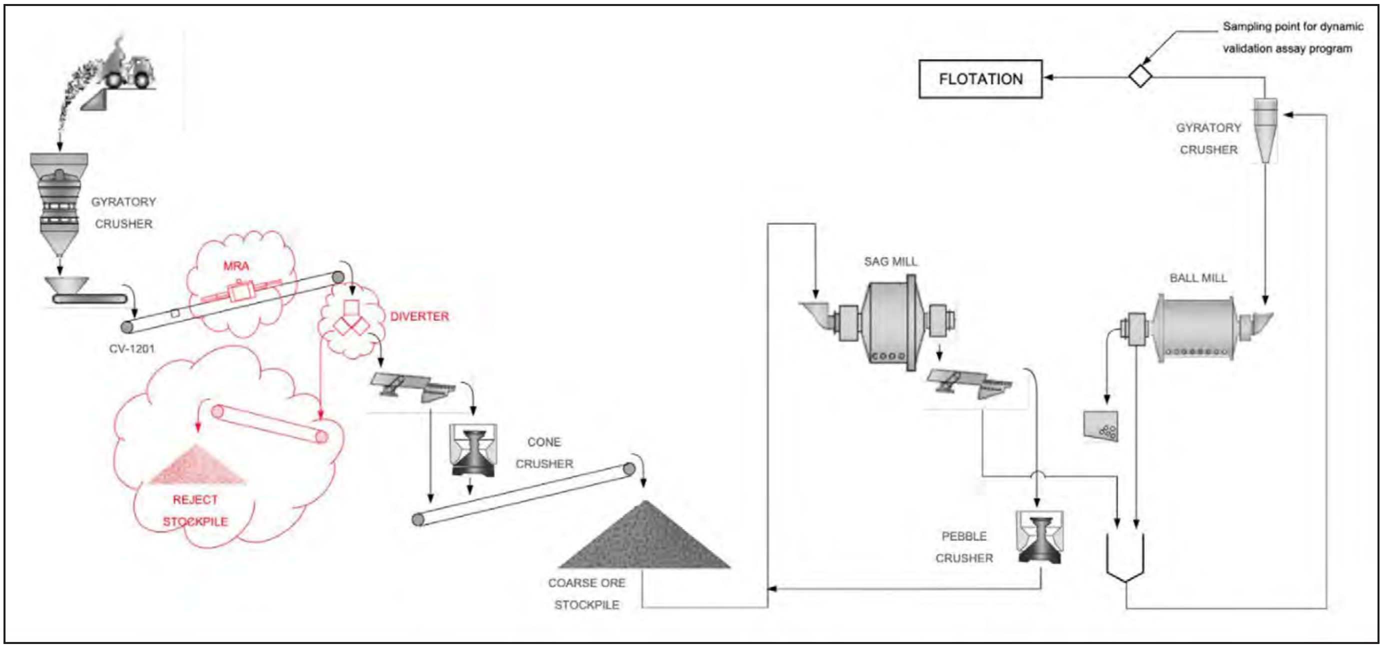


Figure 3. Process flow diagram of existing KMP primary sulphide crushing and grinding circuit with retrofitted BOS equipment shown in revision clouds and the sampling point for the dynamic validation test indicated (top right)

Figure 4. Kansanshi S2 primary gyratory crusher (far right), discharging to CV-1201, transfer tower and cone crusher (centre) discharging to coarse ore grinding feed stockpile (left). Photo taken prior to analyser and bulk sorting retrofit

with secondary cone crusher, shown in Figure 4. This tower contains transfer chutes which could be modified and upgraded with a customised diverter to enable bulk ore sorting with minimal impact on production. Sufficient clear area to the Northwest of the transfer tower was able to easily accommodate both a reject handling conveyor belt and stockpile. Satellite imagery in Figure 5 shows the area before and after BOS installation.

Magnetic Resonance Analyser

Limited placement on CV-1201 forced installing the MRA 46 meters from the feed end, leaving 67 meters to the discharge point (Figure 6). This measurement is crucial for any BOS system as the sensor-to-diverter time must be at least the measurement pod duration + processing time + half the diverter actuation time. The short measurement interval achievable using magnetic resonance adds to the flexibility

Figure 5. Satellite image of Kansanshi sulphide primary crushing circuit in August 2021 (left) and June 2022 (right), after installation of BOS equipment

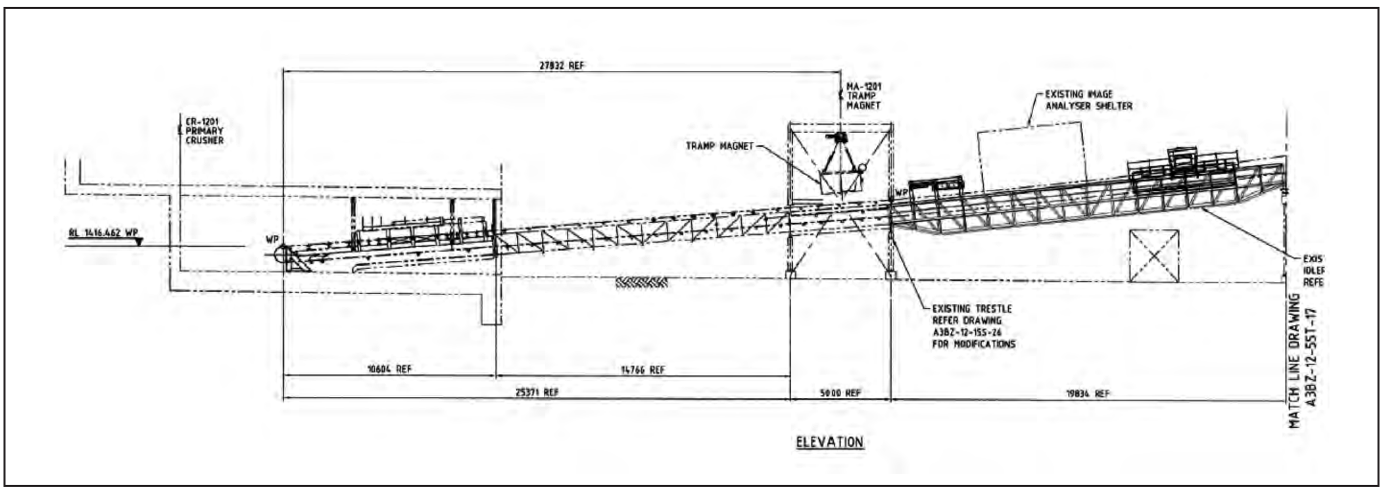


Figure 6. CV-1201 Elevation showing selected MRA installation position relative to feed end

of the system. The 4-second measurement interval in fact allows four pods are fully measured before discharge and is more than adequate.

MRA Design Considerations

MRAs comprise two primary components, the electronics container and the sensor. The electronics container is an air-conditioned shipping container, 10 feet in length, and houses the radiofrequency power supply, amplification, conditioning and control systems. The electronics is positioned within 10 m of the sensor and connected by several cables.

The sensor is an approximately cylindrical shaped radiofrequency antenna, constructed in upper and lower halves, through which the conveyor belt passes. MR sensors are customised to suit the dimensions of the existing conveyor and the ore. The 600–800kg sensor assembly is designed to rest on the existing conveyor belt structure without modification and without the need to cut the conveyor belt (Figure 7).

As is typical for MR sensor installations, the sensor was installed during a scheduled 12-hour shutdown. As a result of COVID travel restrictions, installation was done by KMP personnel at the remote direction of NextOre personnel located in Sydney, Australia.

The sensor aperture dimensions are designed to safely accommodate the ore and achieve a fill factor, calculated as the cross-sectional area of the ore divided by the cross-sectional area of the antenna, of between 10–25%. The design features an opening size larger than the diameter of the largest expected particle size to pass through, resting on top of an otherwise fully loaded belt, without making contact with the sensor. There are no restrictions on the distance between the sensor and the surface of the ore, no restrictions on particle size or moisture content of the ore (Figure 8).

MRA Safety

Interlocks are fitted to all high voltage areas to ensure personnel safety, and all accessible areas adjacent to the conveyor belt have radiofrequency field strength well below public exposure limits as defined in (Australian Radiation Protection and Nuclear Safety Agency (arpansa), 2021) The sensor does not use ionising radiation.

No additional site-specific safety controls were required beyond those which are embedded in the MRA.

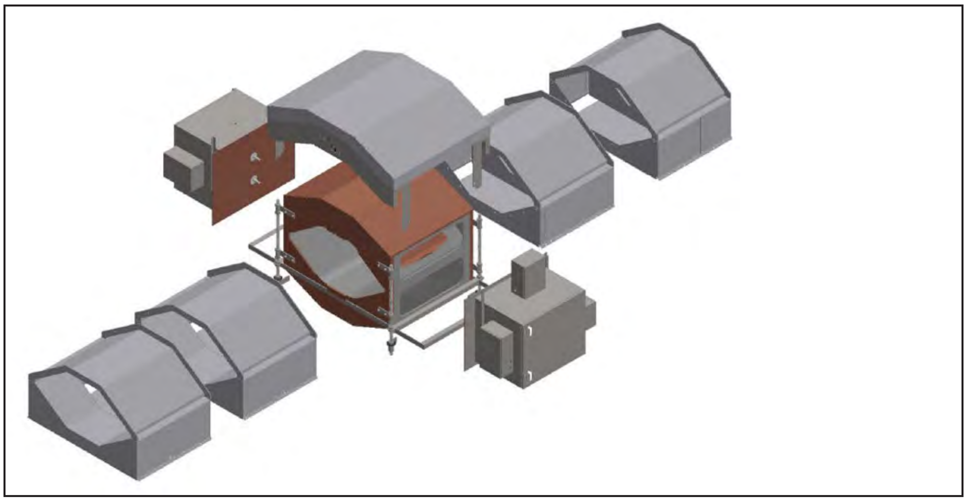


Figure 7. Isometric view of MR sensor major design components

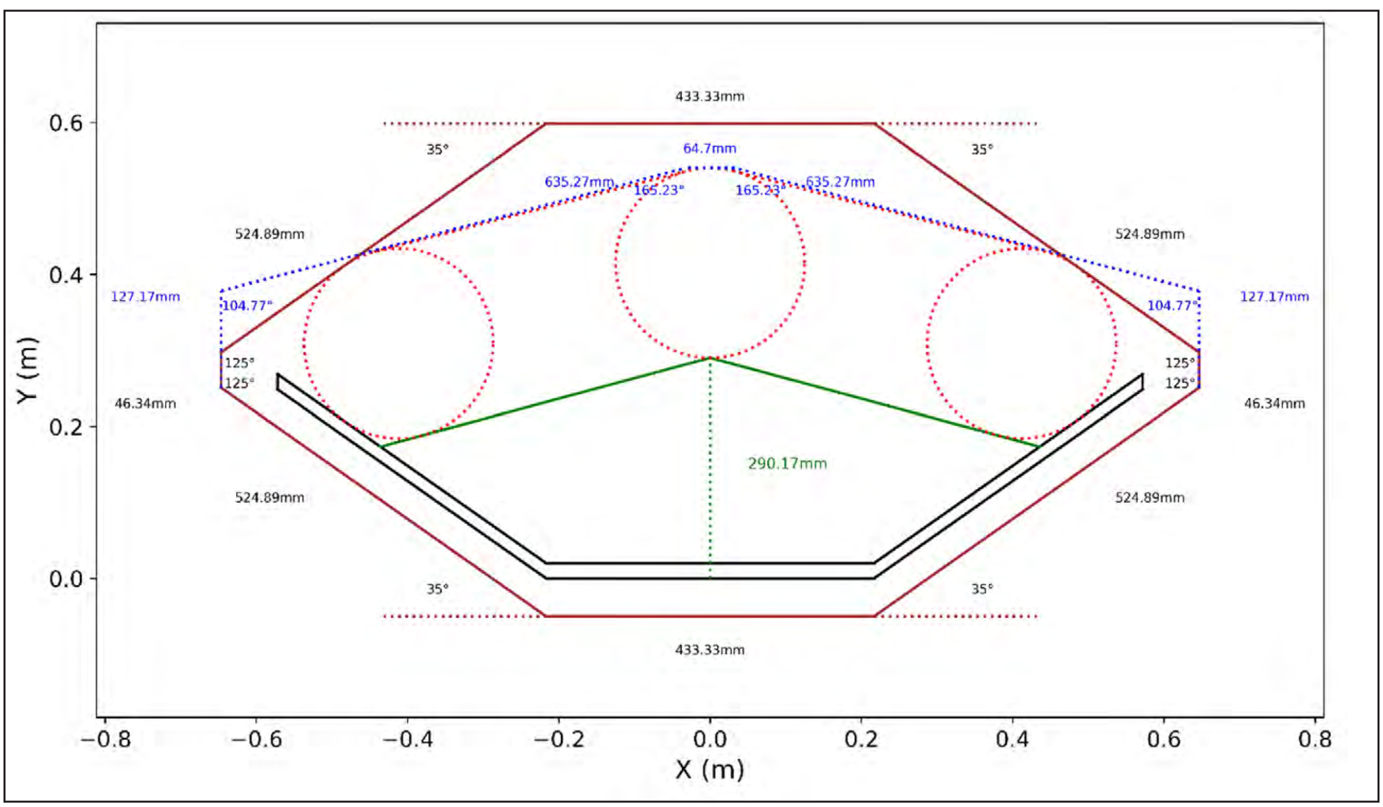


Figure 8. MR Sensor typical cross-section. Red solid line shows minimum aperture design size

Diverter

A hydraulically actuated rock box diverting chute was custom designed for the application by KMP and the existing chute following CV1201 was modified to accommodate the change. The actuation time of the hydraulic mechanism is approximately 2 seconds. After moving from the "Product" position to the "Reject" position, several seconds elapse while a layer of hung-up rock accumulates to form an autogenous layer. The autogenous layer then reports to the Product belt when actuation is reversed. (A video of the diverter test can be accessed at https://www.youtube.com/watch?v=vRLBnGgNmm4.)

Sensor/Diverter Control and Synchronization

A PLC integrated into the MRA electronics container sends signals directly to the diverter gate controller. The direct connection ensures that variable latency is not introduced from external systems and ensures correct timing of pod diversion. A bypass switch controlled by the KMP DCS system allows the KMP control room to enable or disable sorting functionality and preserve the flexibility of the 3 KMP processing lines.

The average speed of the conveyor belt is 3.41 m/s and is highly consistent. The standard deviation of belt speed is 0.12 m/s. There are no other features which introduce variability into the time between sensor and diverter, such as transfer chutes or surge bins.

Synchronization between the sensor and the diverter was fine-tuned by plumbing a water spray over the conveyor after the MRA and integrating an electrical solenoid valve via the MRA PLC. Two signals were programmed into the PLC output, one to the solenoid valve and the second to the diverter controller. A zero second delay was programmed into the solenoid valve signal and a longer delay of approximately 15.7 seconds was initially programmed into the diverter delay, then adjusted such that material wetted by sprays during commissioning reports to the reject conveyor and dry material reports to the product conveyor. This accounts for the swing time and rock box autogenous layer accumulation time to be tested experimentally to have the most precise separation of material by pod. (A video of the MRA/diverter synchronization spray tests can be accessed at https://youtu.be/j3mSk2oUmLE)

Considerations for BOS Using Mineralogical Grade Sensing

MRAs measure mineralogical content, typically of a single mineral per analyser. Therefore, for measurement by MRA to be suitable for use in BOS either:

a. the target mineral or minerals must represent substantially all of the copper bearing minerals in the stream, or
b. the proportions of the target mineral to total copper grade must be sufficiently well understood and reliable in occurrence.

In the KMP Sulphide circuit, chalcopyrite is the dominant copper bearing mineral, hosting over 90% of the copper in the mill feed. The feeds to the other two circuits at Kansanshi, namely Mixed and Oxide, contain a wide range of copper minerals with variable proportions of primary and secondary copper sulphides as well as copper oxides and silicates. Consequently, use of the MRA tuned for chalcopyrite measurement is only suitable at Kansanshi for primary Sulphide ore.

Effective BOS outcomes rely implicitly on the effectiveness of mining and geological functions to separate ore types ahead of the crusher feed points for the respective processing circuits. This reliance on upstream ore assignment is not dissimilar to the three processing stream configuration of the processing plant, as each stream is optimised for recovery of the mineralogy of the respective ore types.

VALIDATION TESTING

Validation testing is undertaken firstly to confirm the sensor is measuring both accurately and precisely and secondly to check that the full BOS system is operating effectively and as designed.

Sensor accuracy (the difference between the measured value and the true value) is tested by conducting measurements of samples which are representative of feed and comparing these measurements to assays of the same samples.

Sensor precision (consistency or reproducibility of measurements) is tested by performing repeated measurements of the same samples and characterizing the standard deviation of the measurement. This test is also used to determine the lower detection limit of the sensor, which is the 3-sigma, or 99 percentile, value above zero.

A separate type of test is necessary to evaluate overall system functionality and ensure subsystem are operating properly and synchronised with the other components of the system. The separation of material by grade using BOS is statistically impossible to achieve accidentally, but the grades of the two streams can be relatively straightforward to confirm. This can be done through sampling and assaying of the streams by laboratory analysis, or using a method pioneered by Kansanshi by campaign processing of a test reject stockpile. This validation program for the Kansanshi BOS system, as described below, is believed to be truly novel and the successful results achieved are believed to be unprecedented at this scale.

Static Testing

One or more pre-characterised samples are measured repeatedly to characterise MR measurement precision and accuracy.

Procedure

MRA measurements are produced for each sample and assays are performed on subsamples thereof. The MRA produces a measurement for 100% of the sample material in each case, whereas standard assay techniques are performed on samples typically of only a few grams. Proper sampling and assaying methodologies must be maintained to minimize error introduced as a result of measuring different samples.

To reduce the potential for error, ore samples were crushed finely and pre-characterized by Atomic Absorption Spectrometer (AAS) assay at the KMP site laboratory.

MRA Sample Measurement Procedure

Each sample was made up of three bags which were laid out along the 1.1 m length of the sensor to approximately replicate typical ore loading of the sensor. While the conveyor belt was stopped, and with a NextOre representative either remotely or physically present, the MRA was disabled and samples positioned manually inside the MRA sensor opening area. The MRA was then restarted and operated for approximately five minutes to collect measurements of the sample in 4 second intervals for approximately 300 individual measurements per sample.

Static Testing Results

Figure 9 shows results of static measurements for accuracy with an R^2 value of 0.98.

One low-grade outlier was removed from the data set. Two high grade outliers are observed but have been retained in the results. It is observed that some particularly high conductivity ore produces an attenuation effect in response signal at high grades. Pods of feed grade exceeding 4.0% copper were regularly observed during operation of the MRA at Kansanshi. These high grades exceed sorting cut-off grades by a sufficiently large margin that the attenuation does not impact sorting results.

Figure 10 shows signal magnitude of MRA measurements over time during the sample testing program. Data in the chart is made up of successive 4-second measurement intervals and the observed noise gives measurement precision. When converted from magnitude to copper grade percentages, this grade variability represents a 1-sigma standard deviation of 0.014% copper and a 0.045% copper lower detection limit.

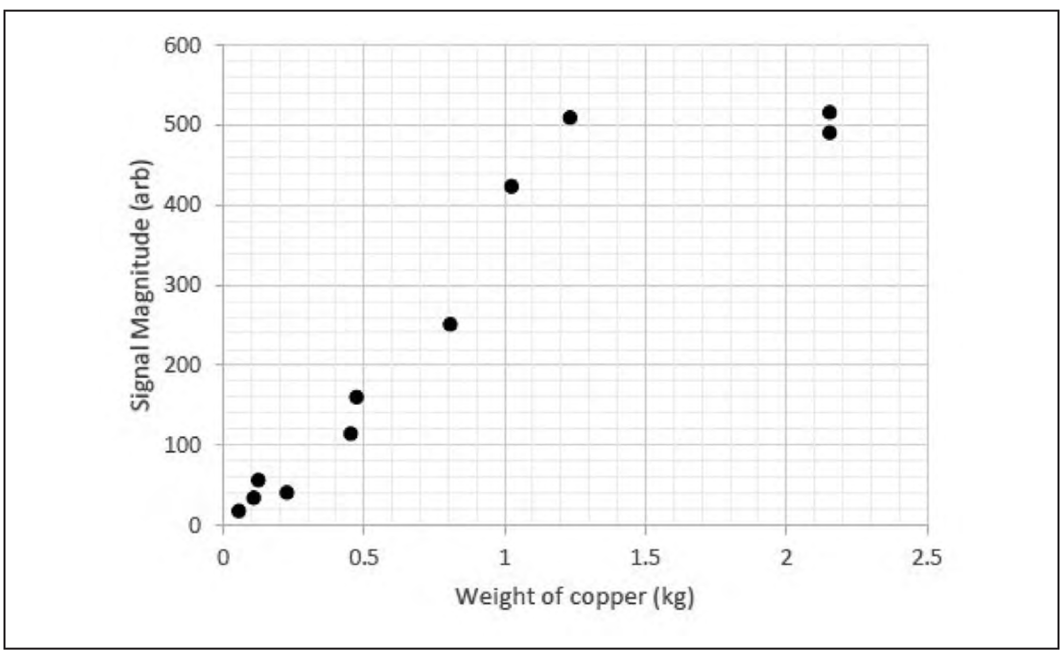


Figure 9. Measurement of signal magnitude for crushed ore samples compared to the KMP metallurgical laboratory

Metallurgical Reconciliation

Further validation was performed by comparing daily average copper grades as calculated by the MRA with metallurgical reporting balances for the primary copper sulphide feed line. As shown in Figure 4, the sampling point for metallurgical sample collection is located at the cyclone overflow following the primary sulphide comminution circuit. The coarse ore stockpile ahead of the SAG mill fluctuated in size up to 70,000 tonnes, or just over 1 day of full feed to the circuit. This fluctuation could not be reliably monitored and calculated, and consequently the comparison of MRA grades to metallurgical balances can only be used roughly, and only over a sufficiently large time scale.

Figure 11 shows 16 days of 24-hour average grade comparisons between MRA grade readings and KMP metallurgical reporting using assays of samples collected from the cyclone overflow sampling point.

Dynamic Testing

KMP applied a novel methodology for full-scale validation procedure not seen at any other operation. BOS activities were undertaken for a period of approximately two weeks prior to 19 May 2021. During this period of time, a diverter cut-off grade of 0.20% copper was applied and an estimated 10,000 tonnes of reject material reported to the

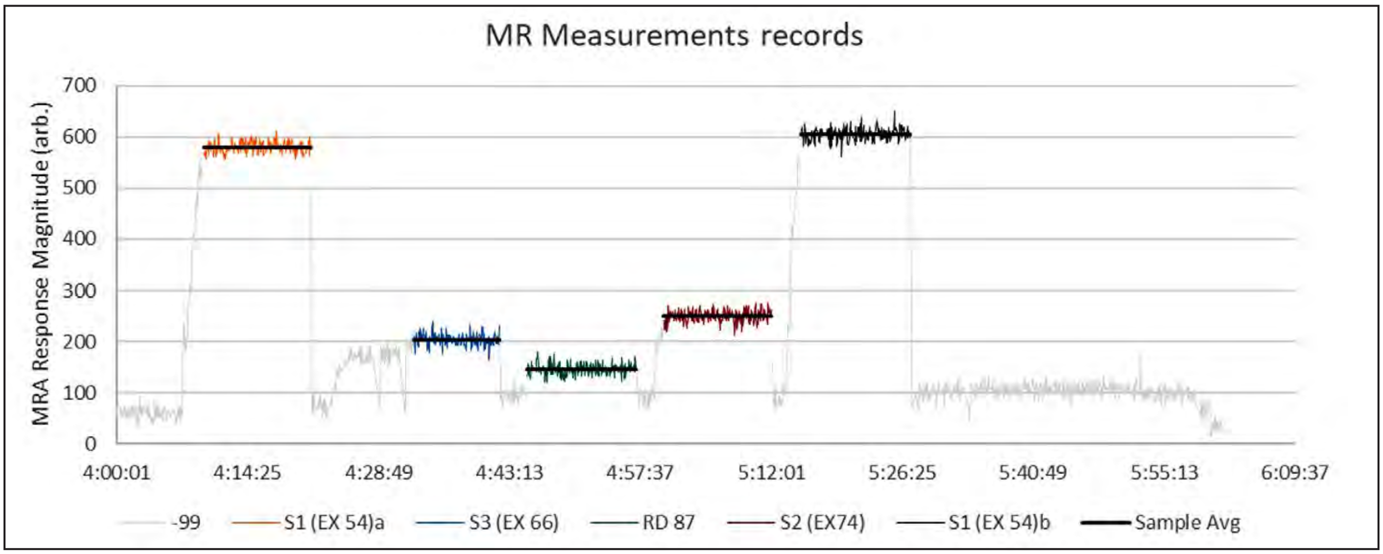


Figure 10. Example measurement of signal magnitude for crushed ore samples over time for calculation of precision. Note these tests were performed with a layer of accumulated fine ore at the bottom of the sensor, leading to a residual signal magnitude observed between sample measurements

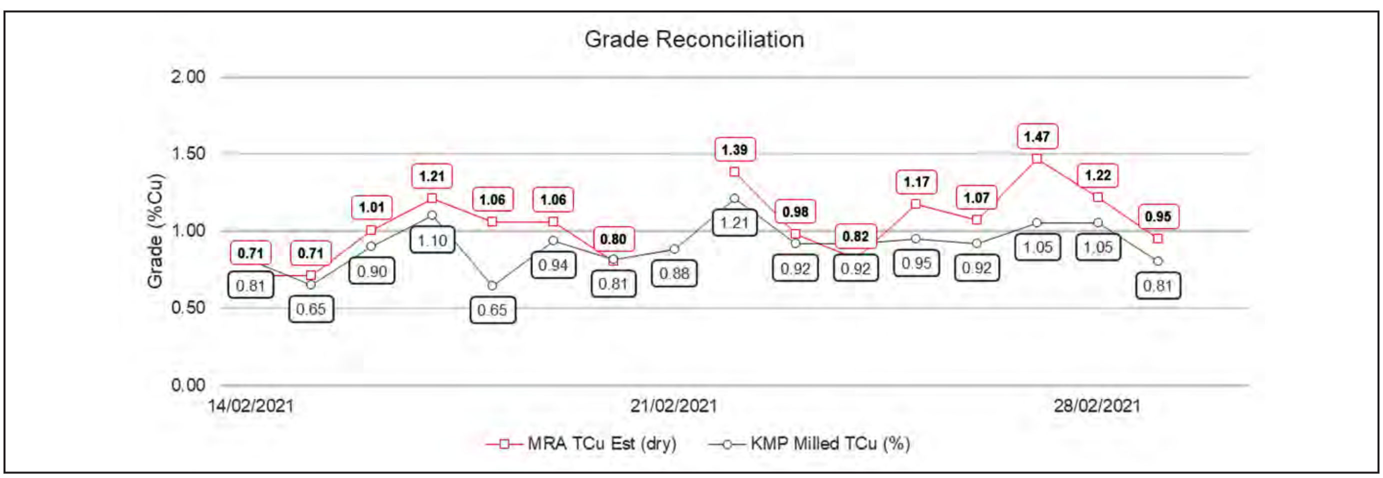


Figure 11. MRA grade measurements versus KMP metallurgical sampling and assays for 24-hour average periods. Maintenance occurred on 21 February and therefore no MRA data was available for the day

Figure 12. Approximately 10,000 tonnes of BOS reject material accumulated at KMP and used for validation testing program

reject stockpile. (Figure 12) Average grade for this reject material as reported by the MRA was 0.16% copper.

During a campaign of ~1 hour and 45 minutes, the BOS functionality was disabled and 5,000 tonnes of the rejected material was fed back to the gyratory crusher of the primary sulphide processing circuit, making up the entirety of the feed material. The coarse ore stockpile was drawn down in advance of the campaign such that the reject material would report without any delay and with minimal cross-contamination to the grinding stage of the primary sulphide circuit.

Samples were collected every five minutes for the duration of the campaign from the cyclone overflow sampling point of the grinding circuit (refer to Figure 4). Samples were assayed (AAS) for total copper content. The chart below shows measurements collected by MRA and corresponding sample assay grades for the campaign period, as well as the periods immediately preceding and following the campaign.

Figure 13 shows 24 hours of grade data from MRA along with sample assay data for 19 May during the validation campaign. Sample assays from the cyclone overflow decline for the duration of the campaign and reaching a minimum grade of 0.17%Cu before climbing again after completion of the campaign.

The results of the campaign demonstrate the effectiveness of the BOS operations and are indicative of proper functionality across both the analyser and diverting equipment. Resulting data is consistent between the various measurement methods: MRA % copper measurements align with the cyclone O/F sample assays collected during the trial. The sample assays exhibit a slightly positive bias above the MRA, decreasing over time, as is expected considering recirculating loads of fresh ore fed prior to beginning of the campaign. Further, the six-hour composite assay from the Vezin sampler is consistent with both MRA and O/F samples.

BULK SORTING RESULTS

Significant heterogeneity was observed in MRA grade measurement data at the Kansanshi mine, supporting expectations based on the complex geological setting of the ore. Operational mixing inherent in the Kansanshi operation is minimal and represents an ideal setting for BOS. Ore is loaded to trucks by shovels in the bench and tipped directly to the crusher feed pocket, generally with no rehandle although stockpiling does occur on occasion. As a result, heterogeneity is preserved and strong bulk ore sorting results can be achieved with installation of the BOS system after the primary crusher.

Figure 14 shows typical grade fluctuations over a 24-hour period. An example, theoretical sorting cut-off grade example is overlaid along with calculation of mass and metal recovery. MRA grade measurements were observed to frequently fluctuate at Kansanshi below 0.10% and above 2.50% copper within a matter of hours.

Mass recovery and metal recovery of BOS can be adjusted by changing the BOS diverter cut-off grade. To

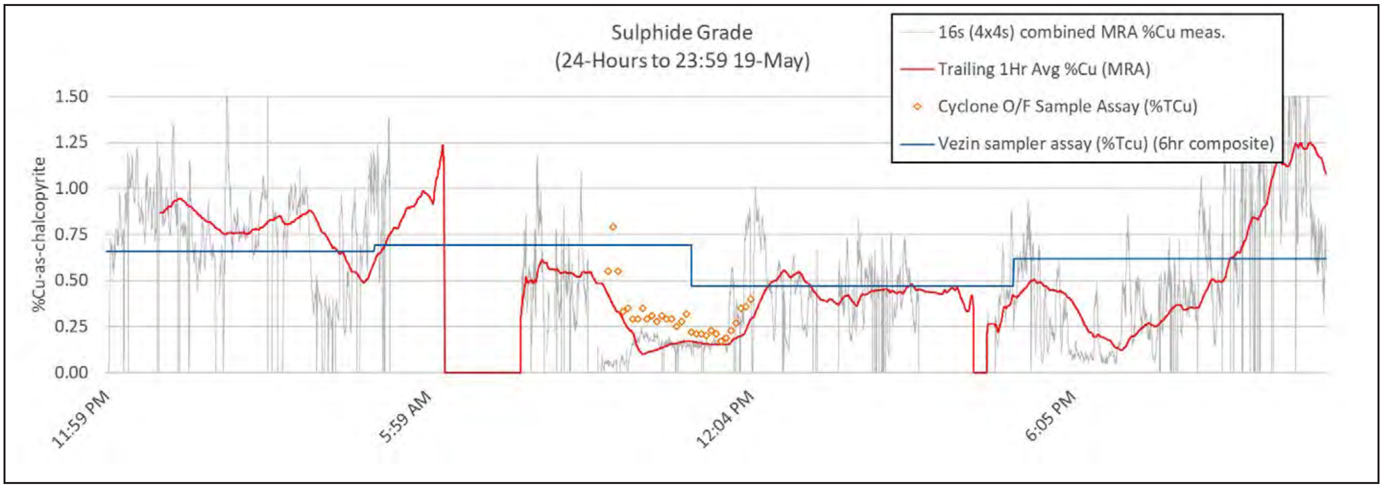


Figure 13. MRA trailing average grades (16 seconds and 1 hour) and sample assay grades

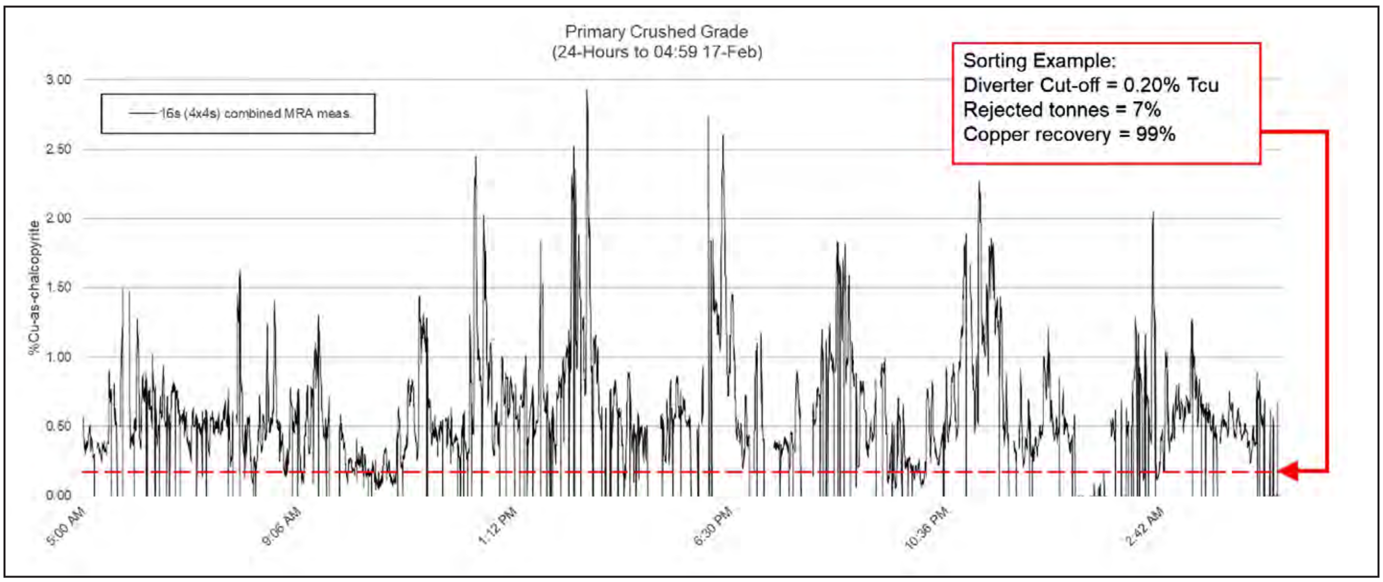


Figure 14. Time series MRA grade data showing example of typical grade fluctuation observed over a 24-hour period. Note that the chart shows an average grade of 4× MRA measurements, each of 4 second intervals, to more easily visualise the data

illustrate the range of potential bulk ore sorting outcomes, MRA grade data is collected for a period and a range of sorting cut-off grades applied, with mass and metal recoveries calculated for the data set. This allows the BOS to be optimised continually to suit the characteristics the surrounding operation.

Results of this analysis for a one-month aggregate period are shown in Figure 15. The results are contextualised by comparing with "Excellent," "Good," "Moderate" and "Poor" results observed by NextOre either in other BOS installations or in heterogeneity study results for other mining projects and mining operations conducted previously by NextOre and CSIRO.

CONCLUSION

The Kansanshi BOS program is a significant milestone in the development of sensor-based BOS technology. This scale of sensor-based on-conveyor BOS has not previously been documented and is believed to be the largest installation of its kind. The BOS system has been proven to operate effectively at a rate of 2,800 tonnes per hour, delivering measurable levels of ore grade preconcentration and demonstrating the potential for this technology to be successfully deployed at the scale of typical medium and large copper mines.

The validation methodology used for the Kansanshi BOS program is also considered to be a world first. This

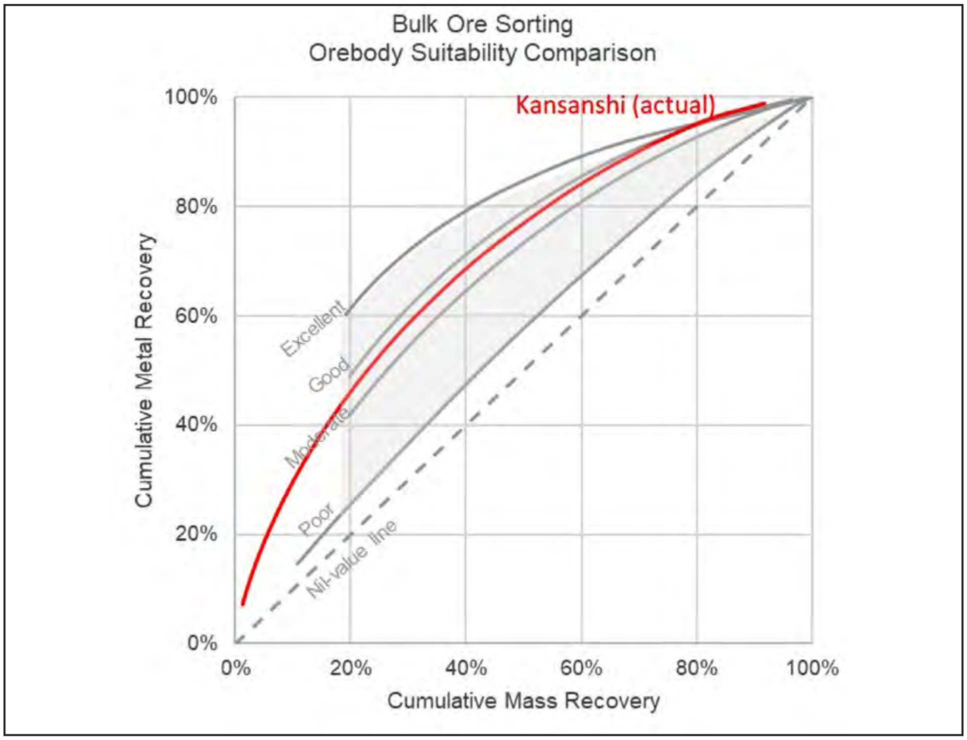


Figure 15. Calculated range of BOS mass and metal recovery scenarios achievable at KMP by varying BOS diverter cut-off grade for November 2022 aggregated MRA measurements

methodology involved feeding rejected material back into the processing circuit and measuring the impact on copper recovery. This approach provides a more rigorous test of the BOS system than traditional methods, which typically rely on static testing and do not evaluate system functionality as a whole. The Kansanshi validation methodology should represent a new standard for proof of BOS systems.

Overall, the Kansanshi BOS program is a success story that demonstrates the potential of sensor-based BOS to improve the efficiency and profitability of mining operations. The scale of the project, the effectiveness of the BOS system, and the innovative validation methodology all make the Kansanshi BOS program a significant step in the development of sensor-based BOS technology.

ACKNOWLEDGMENTS

Evans Simpemba, Plant Metallurgist (KMP)

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