NEAR-INFRARED SPECTROSCOPY (NIRS) SORTING IN THE UPGRADING AND PROCESSING OF SKORPION NON-SULFIDE ZINC ORE

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ABSTRACT

In 2008 Anglo American sponsored a research project at RWTH Aachen University to assess the feasibility of the use of near-infrared spectroscopy (NIRS) for ore waste discrimination at the Skorpion zinc mine.

The Skorpion mine is an open pit zinc mine located in Namibia, owned by Anglo American with an annual production of 150 000 t/a of super high grade pure zinc. Opportunities for the implementation of NIRS sorting for the Skorpion process exist to upgrade currently subeconomic material, including the marginal dump (over 2000 000 tonnes, av grade of 2.5 per cent Zn).

NIRS sorting is not yet implemented or established in the minerals industry however it is a proven technology in the plastics recycling industry, where more than 2000 NIRS sorters have already been installed. NIRS sorting, a type of sensor-based sorting, is a single particle sorting technique which classifies the particles based on the absorbed/reflected radiation in the near-infrared (NIR) region. A disadvantage of NIRS is that it is a surface measurement technique, but NIRS sorting shows overall great potential for the minerals industry.

Skorpion ore minerals include zinc bearing phases such as sauconite, hemimorphite, smithsonite, and hydrozincite. These display diagnostic responses in the near-infrared. There are three major absorption features that characterise the reflectance spectra of the ore bearing minerals. These are due to OH and H_2O molecular bonds. The spectral response of the waste material is caused by other minerals such as non-zinc-bearing clay minerals, calcite and impure quartz.

Test work showed that it is theoretically possible to separate ore material from most waste material based on spectral response in the NIR region. In addition to upgrading material by removal of waste it is also potentially feasible to classify the material based on zinc grade. A tentative correlation between zinc grade and spectral response seems to exist for the sample test suite in the NIR region.

Keywords: sensor-based sorting, near-infrared spectroscopy, NIRS sorting, Skorpion zinc mine

INTRODUCTION

Sensor-based sorting can help to overcome problems in some of the most critical areas of modern mining and mineral processing: energy consumption, mineral reserves, water consumption and environmental impact. Most of the solutions are based on the fact that sensor-based sorting allows a pre-concentration step (waste removal at an earlier stage) (Wotruba and Pretz, 2008). Sensor-based sorters can be implemented in different mineral processing stages to fulfil various tasks. Sensor-based sorting is applied here as an umbrella term for all applications where particles in a material flow are singularly detected and evaluated by a sensor technique and then rejected by a mechanical process (Riedel and Wotruba, 2005). The basic aim of sensor-based sorting is to improve the grade and recovery of the ore stream flowing into subsequent mineral processing operations (eg. Death, 2005). A number of different technologies are applicable to sensor-based sorting. These include optical, electromagnetic, Dual Energy X – Ray transmission, XRF, neutron activation and near-infrared spectroscopy (NIRS).

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In 2008, research sponsored by Anglo American and conducted at RWTH Aachen University was undertaken to assess the feasibility of the use of NIRS sorting, an art of sensor-based sorting, in the upgrading and processing of Skorpion non-sulfide zinc ore.

NIRS SORTING IN THE MINERALS INDUSTRY

During the past three years the Department of Mineral Processing of the RWTH Aachen University has been investigating, in cooperation with TiTech and Anglo American, the technical feasibility of the implementation of NIRS sorting in mineral processing.

Mechanical principle

NIRS sorting is one type of sensor-based sorting. Figure 1 shows the fundamental principle. The main sub-processes of any sensor-based sorting operation are as follows: material preparation, material presentation, material sensing, data processing and material separation (Wotruba, 2006). The basis for sensor-based sorting is the material preparation and presentation, which prepares the material to be properly detected by the sensor. A good balance between the liberation particle size and particle size range needs to be created to optimise the tonnage throughput. Within a single particle sorting technique the throughput is linearly depending on the average particle size. After the preparation and presentation the physical properties on which the discrimination of the particles is based needs to be sensed and evaluated (Riedel and Wotruba, 2005). In the case of NIRS sorting this physical property is the reflectance of near-infrared (NIR) radiation, which is emitted by the source above the belt. Certain wavelengths excite molecules to oscillate which are therefore absorbed. The other part of the radiation is diffusely reflected and directed to the detector unit. The result is a spectrum of the reflectance intensity above the wavelength. The current state of the art is the measurement of 640 000 NIR spectra per second per meter conveyor belt and a minimum grain size of 6 mm. After detection the data-processing system evaluates and classifies the data based on separation criteria (spectral differences). This all has to happen in real time processing speed. According to the evaluation the particle will be classified as belonging to one of the two selected classes and a signal will be send to the ejection area. The mechanical separation of ore and waste can usually be achieved using a carefully pneumatic blast produced by and array of high–speed air valves. A conservative calculation of the capacity of a sensor-based sorter can be made by the average particle size times the band width (Riedel and Wotruba, 2005). In the case of Skorpion, the average particle size is estimated on 110 mm and the working width of 1200 mm which means a conservative capacity of 130 t/h (Robben, 2009).

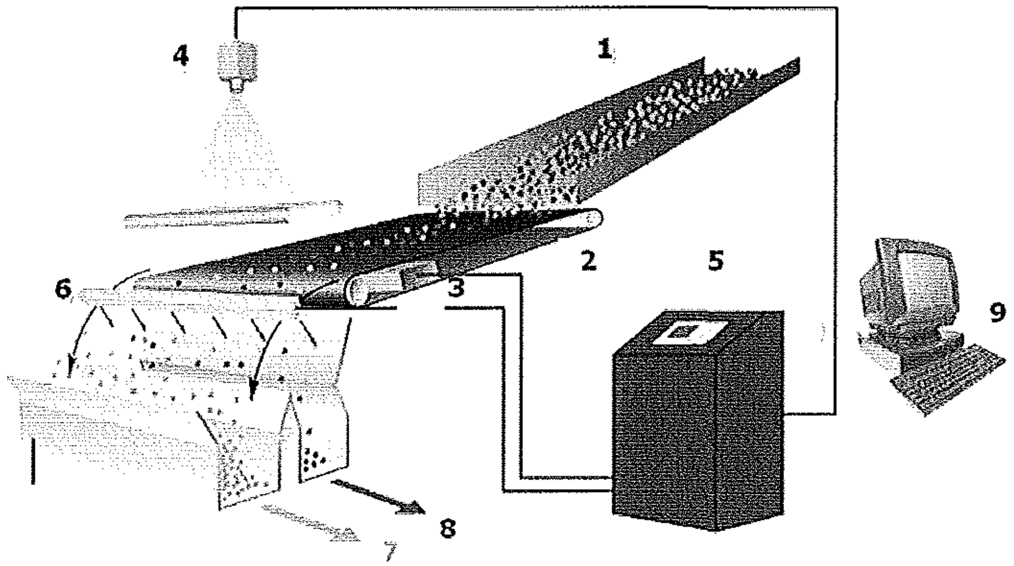

FIG 1 - The fundamental principle of an NIRS sorter. 1) preparation and presentation, 2) acceleration on belt 3 m/s, 3) optional electromagnetic sensor, 4) NIR sensor, 5) data processing, 6) ejection area (air pressure valves), 7) accept stream, 8) reject stream, 9) network interface for central control.

Minerals industry

NIRS sorting is not yet implemented in the minerals industry. Recent tests on ores, including ores inseparable with traditional sensor-based techniques, show encouraging results with NIRS sorting, which is based on a primary property of the minerals (the specific and individual spectral response in the NIR range) (Wotruba, Robben and Balthasar 2009). NIRS sorting has its roots in the recycling industry, particularly recycling of plastics; more than 2000 NIRS sorters have already been installed with high technical availability and NIRS has gained increasing interest, especially in process control applications. The method of near-infrared spectroscopy is known to be applicable to inorganic minerals as a result of extensive mineral exploration and deposit evaluation work (analysis of drill cores, portable spectrometers). Reflectance spectroscopy is also widely used in the remote sensing discipline and geologists have recognised that this method has far reaching applications in, for example, lithology mapping (Thompson, Hauff and Robitaille, 1999). This is especially because with NIRS it is possible to create a fingerprint of a sample, which is directly related to the mineralogical composition. The fingerprint is actually the spectral response on the NIR source; a mineral depending part of the electromagnetic radiation is absorbed which results in a spectrum with absorption features. A major amount of minerals can be classified based on their spectral response in the NIR and most diagnostic absorption features occur in the region between 1300 nm and 2550 nm (eg. Clark, 1999). The main molecule bondings which cause absorption features in the NIR region for minerals are given in table 1.

TABLE 1

Main molecule bondings causing absorption features in NIR (Clark, 1999; Clark, 1995; Thompson, Hauff and Robitaille, 1999).

Molecule bondings	Absorption features in NIR (nm)
Hydroxyl (OH)	1400 (1550, 1750, 1850)
Water (H_2O)	1400, 1900
Carbonate (CO_3)	2300 – 2350, (1870,1990,2155)
Ammonia (NH_4)	2020, 2120, 1560
FeOH	2230 – 2295, (2330)
MgOH	2300 – 2360, (2250)
AlOH	2160 – 2220, (2200)

Minerals that do not have structural OH, H_2O, CO_3 or NH_4 will not display strong diagnostic absorption features in the NIR region. The spectrum of samples dominated by other minerals can however display absorptions associated with non-diagnostic secondary components;

- Broad water features caused by fluid inclusions or surface moisture
- Clay absorptions from present weathered material and feldspathic components.

If differences in spectral response or fingerprints are large enough for detection, identification and classification based on the mineralogical composition is possible. Differences in absorption features make material sortable with NIRS sorters (Wotruba, Robben and Balthasar, 2009).

Shape, temperature, and moderate moisture content do also cause differences in absorption features but these are smaller than the difference caused by chemical variance. Test work showed that the influence of shape, temperature and moderate moisture content do not hinder the sorting. Other test work showed very promising results including the possibility of sorting barite and fluorite from calcite and dolomite. The results for sorting marble, talc and borate out of waste material are also very encouraging. If the major components do not show specific absorption features, minor components like alteration minerals can be used as markers for the sorting task as indirect sorting criteria. In addition to direct applications, large potential is expected for the NIRS sensor for numerous indirect sorting tasks (Wotruba, Robben and Balthasar, 2009).

The disadvantage of an NIRS sensor is that it only measures the properties of the surface of the rock, which means that only the minerals present at the surface are detected and the measurement is influenced by dust coatings and hygroscopic water. The spectral responses of the uncoated samples are, with increasing amount of dust, sequentially replaced with those of the coating material.

Hygroscopic water reduces the contribution from other NIR active components. Those influences can for the sorting probably be minimalised with help of software tools and by defining and building up the classification system (classifier) under the same circumstances and conditions under which it operates (Robben, 2009).

THE SKORPION ZINC MINE

The Skorpion mine is a conventional open pit zinc mine located in south-western Namibia, southern Africa. It is owned by the Base Metal Division of Anglo American. Skorpion ore reserves are 21.2 million tonnes with an av grade of 10.9 per cent zinc contained in 140 million tonnes of ore and waste. The stripping ratio of ore: waste is 1: 6.5. The mine was planned to have a 15 year mine life and produce 150 000 t/a of refined zinc metal. The open pit is designed to reach a final depth of 240 m below surface with a 4 per cent cut-off. A minimum average grade of 9.8 per cent Zn must be supplied to the plant to ensure production of 150 000 t/a given the throughput constraint of 174 000 t/a (the refinery cellars are the limiting factor).

The pit is mined in benches of 10 m height. Where required by grade control, benches are split into 5 m or 2.5 m sub-benches. A production drill rig is utilised to drill blast holes and provide chippings for sampling purposes. Broken rock is loaded by hydraulic excavators. The main excavator operates in a face shovel configuration and where selective digging is required, a smaller backhoe is used. Material is tipped according to its classification, on different stockpiles, under which a marginal dump. Skorpion is a relatively unusual deposit since it is a dominantly non-sulfide (oxide) zinc deposit. The ore is leached directly in dilute sulphuric acid to produce zinc sulphate. It is not possible to directly electrowin zinc from the sulphate solution due to the high chlorine and fluorine concentration and other impurities contained in the Skorpion ore, which cause corrosion of the anode and cathode and cathode stripping problems. Solvent extraction provides a buffer against the impurities. Skorpion is the first and only process which makes use of the Solvent Extraction Electrowinning (SX-EW) to process zinc. Super high grade pure zinc (over 99.95 per cent zinc) is produced on site and annual production is 150 000 tonnes.

Stratigraphic sequence of the orebody (Borg *et al*, 2003)

The Skorpion orebody is irregularly bowl shaped and has a relatively flat top. The ore grade can fluctuate between 4 and 30 per cent Zn in the pit. The overburden has already been stripped away. At depth the mineralisation has a relatively sharp and complex (sheared, folded, and locally brecciated) contact with impure limestone and calcareous sandstone in the footwall. The ore grade drops to sub-economic and to background concentrations in the limestone in less than 2 m from the mineralised orebody. The limit of the orebody away from the limestone contact is less well constrained and no significant lithologic or structural control has yet been identified (Borg *et al* 2003). With the right pre-concentration step the potential exist to expand the life of mine.

The orebody is hosted by weakly metamorphosed, quartz-rich clastic sediments. These are generally referred to as arkose and include arkosic sandstone, quartzite, shale and sericite schist. Brecciation occurs frequent in the orebody and brecciated zones often contain exceptionally high grades. A steep dipping zone of sheared-sericite-schist and quartz sericite schist cuts through the orebody and surrounding host rocks roughly following the long axis of the mineralised body (Borg *et al*, 2003).

Present minerals in the orebody

The primary precursor sulfide mineralisation comprises pyrite, sphalerite and minor chalcopyrite with traces of galena. Those minerals can still be found in the pit. The oxidation of the primary sulfides in a near-surface environment by low-temperature meteoric fluids led to the formation of the secondary supergene non-sulfide orebody. The supergene non-sulfide mineralisation includes carbonates, silicates, phosphates and (hydro-) oxides and the main ore minerals are sauconite, hemimorphite, hydrozincite and smithsonite. The minerals have either replaced primary sulfides or have grown in secondary pore space. Other zinc-bearing minerals include phosphates (tarbuttite, scholzite) and oxides (chalcophanite and hydrohetearolite, skorpionite, sphalerite and zincolebithenite) (Borg *et al*, 2003; Kaerner, 2006).

Opportunities for sensor-based sorting in the Skorpion process.

One challenge to solve is the processing of the marginal dump and possibly other currently uneconomic material. At present, sub-economic low-grade ore is stored on the marginal dump, next to the pit. The bulk grade of the marginal dump is less than 5 per cent zinc, over actual grade varies from 1 per cent to economic. The economic mineralisation needs to be separated so that the material can be reliably fed into the conventional processing plant. To process the marginal dump and currently uneconomic material a technically feasible and economically viable method needs to be developed to classify and upgrade the material.

Another challenge to solve is the identification and classification of sub-economic and economic ore by the direct detection and quantification of zinc bearing minerals. This may allow direct assessment of grade.

The existing challenges described above lead to possible opportunities for sensor-based sorting. The pre-concentration step could increase the zinc production of Skorpion by up-grading/processing currently uneconomic mineralisation. The sensor-based sorter could also detect different grades of zinc bearing material allowing optimal stockpiling and blending.

The amenability of the Skorpion deposit to NIRS sorting

The most important zinc bearing minerals occurring in the Skorpion orebody, smithsonite, hemimorphite, sauconite and hydrozincite, are NIR active, which by near-infrared sensors can be detected (figure 2). The three major absorption features that characterise the reflectance spectra of those minerals are due to OH and H_2O molecular bonds. This is a paper quoting results of a feasibility study done on the implementation of NIRS sorting in the process of Skorpion zinc ore (Robben, 2009).

TESTWORK

To test the amenability and feasibility on the use of NIRS sorting to process Skorpion zinc ore, a suite of representative samples was collected on-site from the Skorpion mine. Test work on the samples with a desktop spectrometer and an NIRS sorter was done to investigate the detectable differences in NIR activity between ore and waste material. The total number of samples is 250, 145 out of the pit, 75 from the marginal dump and 30 samples of zinc bearing minerals. The identification of the collected samples has been done with the pit geologist. The accuracy of this system is therefore dependant on human error. To make the implementation of the NIRS sorter technical feasible, it was considered

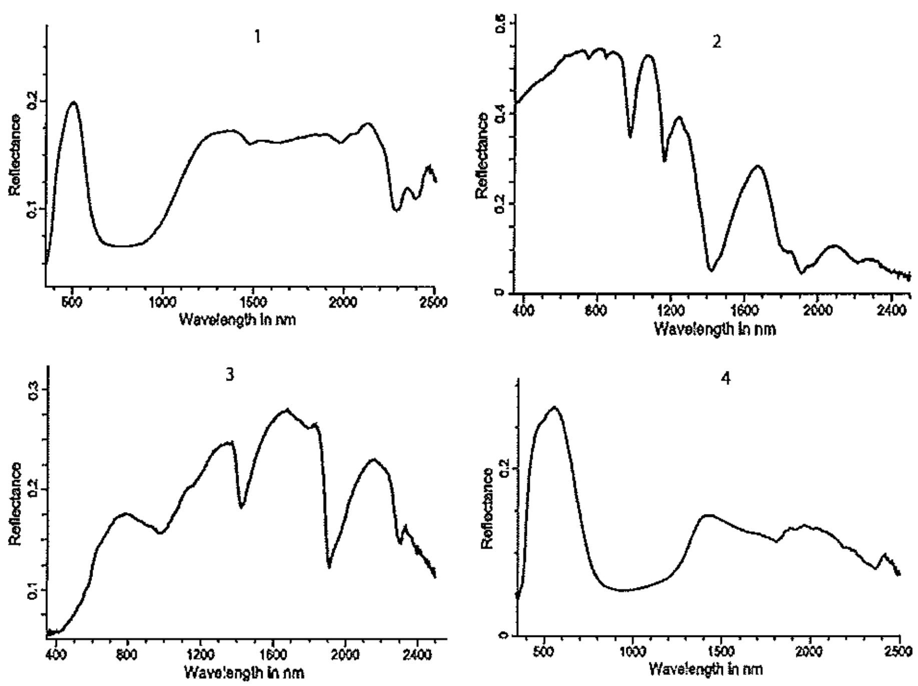

FIG 2 - Reflectance spectra of zinc bearing minerals: 1, smithsonite; 2, hemimorphite; 3, sauconite; 4, hydrozincite (McConachy *et al*, 2007).

useful to retain the mine classification, namely the rock type groups Arkose (ARK), Banded Shale and Arkose (BSA) and Black Shale (SHB) which are all hosts to the zinc bearing minerals. Overburden (OVB), Sheared-Sericite Schist (SSS), Quartz-Sericite Schist (QSS), Rhyolite (RHY), Amphibolite (AMP), Quartz-biotite-schist (QBS), Limestone (LST) and Calcarenite (CALC), Manganese (MAN) and Quartz (QUA) are all classified as waste and therefore these need to be discarded.

Spectra of inhomogeneous material

The NIR spectra of the samples were recorded with a desktop spectrometer, an FT-IR spectrometer from the Bruker TENSOR™ series, manufactured by Bruker Optics Inc. The Tensor 27 is designed for the routine lab as well as for demanding analytical laboratory applications. The external sphere module permits direct reflectance measurement of large samples. The region of measurement for the NIR extends from 700-3000 nm. The NIR source is a Tungsten halogen lamp which has optimal performance between 1000-2500 nm. The installed beamsplitter, CaF_2 VIS/NIR, is efficient in the VIS and the NIR. The detector, the PbS detector is able to detect a signal between 1000-2632 nm. Therefore the detected wavelength range during the measurements was between 1000-2632 nm (10 000-3800 cm^{-1}).

The objective was to characterise the samples by classifying them into groups based on spectral response. The sorting opportunities would be technically feasible if the obtained groups correlate to rock type and/or zinc grade. As stated previously, the Skorpion ore bearing material contains minerals with molecular bonds which do cause absorption bands in the NIR region and there are three major absorption features that characterise the reflectance spectra. Because those absorption features are also clearly visible in inhomogeneous material, the application of NIRS sorting has potential. The absorption features are overtones and combinations of fundamental features that occur at longer wavelengths due to vibrational processes in the OH and H_2O molecular bonds. The spectral response of the waste material is mostly caused by the NIR active minerals as non-zinc bearing clay minerals, calcite and impure quartz. Possible separation between ore and waste material can therefore take place based on NIR active minerals and not only on water absorption bands caused by hygroscopic or free pore water. The spectra of the arkose samples show dominant the presence of sauconite, especially because of the deep asymmetric feature around 1900 nm and the sauconite feature around 2345 nm. Diagnostic features of other zinc bearing minerals are not clearly visible in most other samples, which does not necessarily mean that those minerals are not present in the heterogeneous material. It may mean that the features are not strong enough, do not occur in mixed material, overlapped by other features or the quantity of the minerals in the material is not high enough for detection. In some spectra diagnostic absorption features of tarbuttite and smithsonite are clearly visible. In these cases, the mineral is also macroscopically visible in the sample.

Besides the upgrade (pre-concentration by discarding waste material) it is necessary to classify the material on grade, because only higher grade material above a defined cut off can be fed into the conventional mine process. It was investigated if a more detailed sub-division within the ore bearing material is possible. A correlation between zinc grade and spectral response appears to exist for the tested suite of samples. A linear correlation between the zinc grade and the ratio between the depth of the 2210 nm and the 2345 nm features is found for the spectra of the ore samples. The 2210 nm curve is caused by a non-zinc bearing smectite and the curve around 2345 nm is caused by sauconite.

Test work NIRS sorter

More test work was conducted with the PolySort manufactured by TiTech GmbH. The PolySort is a NIRS sorter designed specifically to sort polymers or mixed plastics by material properties. With its NIRS sensor, the PolySort detects the characteristic NIR wavelength reflected by illuminated objects at two wavelength ranges lying roughly in between 800 and 1800 nm. Based on the characteristic of the absorbed infrared wavelengths the material can be sorted. The working width of the machine can vary between 600-2800 mm. The manufacturer claims the sortable object size range to be between 12-300 mm. The PolySort first needs to be trained with pre-classified (robust and clearly identified) samples. Groups are formed by statistical means and applied into the sorting algorithm, referred to as the classifier. The classification result can be improved by various image processing operations which take into account the neighbourhood of a scan point.

Homogeneous material is preferable for the sorting. The spectral response of heterogeneous material, which is the normal situation in mining, is much more complicated; wavelength shifts, overtones, overlapping of the absorption features etc. and mixed spectra occur. All this spectral variation needs to be taken into account during the design of the classifier. Mixed spectra are caused by diluted minerals, contact zones of different rock types (with different mineral content) and the presence of water (hydroscopic and free pore water). Increase in the required spatial resolution and the inclusion or "teach-in" of more varieties in the classes of the classifier can improve the sorting result. If the spatial resolution is too low it can cause mistakes in the classifications, especially for small heterogeneous samples.

The classifier for the Skorpion sorting task was built up based on a training sample suite of 35 samples. The training samples were chosen based on their zinc grade, their spectral response and their representativity in terms of the rock type groups found in the mine. Different results are expected from the test work with the PolySort in comparison with the Tensor 27 because off the differences in detection range. The sensor of the PolySort has a smaller detection area but better classification/separation might be possible because of the mathematical/statistical method used for the classification.

The training suite, consists six rock type classes, with 5 pieces for each class. A non linear Support Vector Machine was used to solve the classification problem. The remaining marginal dump and pit samples were sequentially placed on a moving conveyer belt. The samples were scanned perpendicular to the conveyer belt on a line. Decisions regarding which rock type group the material belonged to were based on the characteristics of the reflected NIR wavelengths and if needed the air valves were activated. For this test work the air valves were activated for waste material. The classification result was improved by taking into account the neighbourhood of a scan point (the 4x4 filter). The software was configured to suppress ejection in a neighbourhood if ore material was detected, to receive a high recovery.

The PolySort classified 163 samples (77 per cent) in the right rock type class and 48 wrong which resulted in a recovery of 85 per cent zinc in a mass pull of 46.4 per cent for the marginal dump material and a mass pull of 71.1 per cent for the pit samples. Optimalisation of those results is possible by further adjusting the classifier (make the training sample suite more robust and larger), setting changes of the filters, increasing spectral and special resolution and enlarge/change the detection area towards the higher region of the NIR.

CONCLUSIONS

At the start of this project, two possible opportunities for the application of an NIRS sorter in the Skorpion process were recognised. These were: Sort and discard the waste prior to the conventional process, including classifying and upgrading the marginal dump and to classify and sort zinc bearing material based on grade. Test work showed that for the set of samples it is theoretically possible to separate ore material from most waste material based on spectral response in the NIR region. This makes it theoretically feasible to sort and discard the waste prior to the conventional process and upgrade the marginal dump. In addition the results show that a correlation exists between zinc grade and spectral response in the region between 2210-2345 nm. This correlation makes it theoretically feasible to classify the marginal dump with a NIRS sorter. The feasibility study undertaken to assess the use of NIRS sorting in the processing of Skorpion zinc ore has clearly demonstrated that NIRS sensor-based sorting can theoretically work at Skorpion, but further technology development and investigation is required.

The feasibility study on the use of NIRS sorting in the process of Skorpion zinc ore, is a successful example of the implementation of the NIRS sorting in the minerals industry. In addition to the known benefits of sensor-based sorters, NIRS also offers the ability to sort on signals that are direct result of measurement of mineralogical composition. It will be necessary to test and characterise every mineral deposit separately to determine if NIRS sorting can demonstrate advantages. We intend to continue collaboration with Anglo American to further research the application of NIRS sorters to accelerate technology development and unleash the potential of this technique to create or add value to existing and potential new operations.

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