Presorting of high grade molybdenum ore – A case for enhanced small mine development

Michael Hitch, Andrew Bamber, Patricia Oka

***Abstract*— With increasing energy and labour costs, and downward pressure on commodity prices, many mines are forced to extract higher grades to remain profitable. Additionally, pressure is increasing on mine operators to reduce their environmental footprint or face public censure, hence traditional approaches such as increasing the mining rate are not attractive. In this environment, operators must innovate to prevent smaller, or less profitable, mines from closing. Data from over eight years of research at the University of British Columbia, and ore recent data from customer studies at MineSense Technologies suggests that previously unrecognized quantities of barren or low grade waste is the norm, rather than the exception in mill feed material globally, therefore an approach that shows remarkable potential to address both of these issues is the pre-concentration of ore by sorting ahead of the mill. Through sensing of the physical, chemical or electromagnetic magnetic properties of ore on a by-particle basis, significant variations in grade can be measured; by exploiting this sensed data identification and rejection of up to 60% waste by mass prior to the expensive process of grinding is possible. Mill feed grade is increased, reducing transport and processing costs, potentially improving plant recoveries, and reducing the amount of waste being sent to the tailings pond.**

This paper presents the results of recent work undertaken to evaluate the potential of optical, x-ray, electromagnetic and density-based pre-concentration methods on ore from the Kuemseong molybdenum mine in South Korea. The work indicated technical and economic feasibility of pre-concentrating the Kuemseong ore. Using the preferred method of optical separation, overall extraction and recovery was vastly improved, with lower operating costs projected at the mine. The result confirms general potential for this strategy to enhance profitability while simultaneously improving environmental performance for small mine assets.

***Index Terms*— Small Mine Development, Pre-sorting, Resource Utilization, Resource Economics.**

I. Introduction

Sustained success in business requires a commitment to innovation and constant improvement in business processes to either drive unit costs down or unit revenues up. This is particularly evident in the mining industry where success is largely supported by either the highest grade or the lowest production cost. In the face of diminishing opportunity for the extraction of high grade ore, and historically low energy costs and freely available capital over the last quarter of the 20th Century, maintaining low production costs has been a key focus, a focus in general involving the production of ever larger tonnages of ore (and waste) with increasingly larger equipment, thereby reducing unit operating costs. However, such increases in economy of scale do not necessarily improve efficiency, simply dilute the inefficiencies, and, in the face of present and increasingly high energy costs, and restrictions in available capital, increasing the production rate to gain the necessary economies of scale, while entrenching such inefficiencies, is becoming less attractive. New means of achieving low production costs while maintaining efficiency through innovation must be found.

Grinding ore into fine particles ahead of flotation or leaching to produce a saleable concentrate or metal is the single largest unit cost at most mines, and the single largest end use of electricity on the planet [1]. Considering the large amount of barren or low grade material present in mill feed, and general low efficiencies of this energy- and cost-intensive unit operations, efforts to pre-concentrate the ore to increase its grade and reduce the amount of material reporting to the grinding facility can significantly reduce energy requirements and therefore cost of grinding, while potentially enhancing metal recoveries by increasing the head grade to flotation or leaching steps. By simultaneously reducing cost, while improving metal recoveries, profitability can be massively increased.

This paper presents data from a test of four pre-concentration processes on a high grade molybdenum ore from a small underground mine in South Korea as a case study for the concept at a small, high grade mine. This testwork was based on pre-sorting the ore to eliminate waste from the mill feed thus increasing the plant head grade. Perhaps more importantly from an operating perspective, pre-sorting would eliminate waste rock at a coarser size, thus reducing crushing and grinding costs at the mine. Eliminating waste in the plant feed also enhances metallurgical recovery in the subsequent flotation stage and also reduces the quantity of tailings reporting to the impoundment facility, which is a significant collective benefit.

II. Preconcentration as a Key Part of Mineral Extraction and Recovery Processes

There is substantial current and historical precedent for this approach. The earliest mining practices extracting native metals and high grade ores incorporated hand sorting or cobbing using visual assessment of individual mined rocks to categorize each as either ore or waste on the basis of physical appearance and properties of each rock, such as: lustre, colour, shape, weight, or

Michael Hitch, Norman B. Keevil Institute of Mining Engineering, University of British Columbia, 517-6350 Stores Road, Vancouver, BC, Canada, V6T 1Z4, +1 604 827 5089 .

Andrew Bamber, MineSense Technologies Ltd, 202 930 Harbourside Drive, North Vancouver, V7P3S7, +1 604 987 9999.

Patrica Oka, Norman B. Keevil Institute of Mining Engineering, University of British Columbia, 517-6350 Stores Road, Vancouver, BC, Canada, V6T 1Z4, +1 604 827 5089.

texture [1]. For such small, early, high grade mines, the benefits of hand sorting were obvious [2]. However, as grades decreased, production scales increased with new approaches such as mechanized mining, and sorting, failing to offer required capacity was abandoned as an approach until the advent of mechanized sorting in the 1920s.

One of the earliest mechanized sorters, the "Sweet Sorter" produced in 1928, was used to separate ores by colour. Following this invention, the "Lapointe Picker" was later developed to pre-concentrate uranium using principles of chromatography in the late 1940s. Radiometric sorting of uranium ores was implemented at Port Radium and Port Hope in Ontario, Canada in 1958 [3], and widely used in South Africa through the 1980s as a substitute for hand sorting of low-grade gold ores. Diamonds are probably the widest known application of sorting, in particular x-ray fluorescence, but literature on the technology is scarce. There are few examples of the application of sorting at a large scale in the metal mining industry, most recently the installation of an Ultrasort conductivity sorter at Kambalda in Western Australia [4], Xstrata's implementation of conductivity sorting at Cosmos, also in Australia, and the installation of a CommoDas "Mikrosort Primary" optical sorter at Amplats' Rustenburg UG2 Section [5]. Dense medial separation, invented by the Dutch State Mines in the 1940s, is in wide use as a primary concentration method in coal and chrome, as well as a pre-concentration method in lead-zinc, and more recently nickel [6]. Typical plants treat material of between 25 – 300mm at rats of between 30-300 tonnes per hour. Largely ore over 1% metal concentration is preferred although successful application of sorting in particular on ores of 0.1% metal concentration is noted[1] [7]. While therefore having found some application in the minerals industry, at these treatment rates, both mechanized sorting and dense media separation have fallen behind current mining practice, where capacity and sensitivity are reported as the least satisfied need of operators. Further challenges to increased acceptance of sorting in the minerals industry are extant, including a lack of understanding of the basic discrimination principles, opportunities for and applications of sorting; perceptions of high capital costs, high unit operating costs, and poor reliability for the technology; a perception that sorting incurs an unacceptable loss of metal; and the traditionally low capacity of sorters when compared to present throughputs of grinding and flotation plant [1].

However, ongoing research into improved sensors (sensitivity) and sorting applications (capacity) are extending the range and diversity of potential applications. Cutmore et al. [8] studied microwave dielectric spectroscopy in a test of principal component analysis (PCA) and artificial neural nets (ANN) to mineralogically distinguish different samples of iron ore. Lane et al. [9] studied the use of optical microscopy to differentiate non-opaque minerals and epoxies. This work was a continuation of the microspectrophotometry (MSP) research by Pirard [10] to develop reflectance standards and measurement of different mineral properties. Kattentidt et al. [11] investigated ore sorting through ore morphology and texture. Bamber [1] covers extensive developments in optical sorting by textural analysis, and conductivity sorting by high frequency electromagnetics. Table 1 summarizes different pre-concentration technologies applicable in the mining industry.

Table 1 - Sensor Technologies and Sorting Applications [12]

Method	Characteristic	Application
Photometric	Surface	Coal, sulphides, phosphates, oxides
Radiometric	Bulk	Uranium, gold
Conductivity	Bulk	Metal sulphides, native metals
Fluorescence	Surface	Metal sulphides, limestone, iron
X-Ray Luminescence	Surface	Diamond
X-Ray Transmission	Bulk	Coal
Electrostatic	Bulk	Salts, halite, sylvite
Magnetic	Bulk	Iron, andalusite, quartz, kimberlite

In developing the value proposition for sorting in the minerals industry, two clear candidates stand out: high grade, high cost mines and large marginal, low cost mines (Figure 1).

High grade, low cost	Large, low grade, low cost
High grade, high cost	Large, low grade marginal

Figure 1 – Optimal Application of Pre-sorting

For small, high grade mines the principal opportunity appears to be increased production from the same operating asset. For large, low grade mines the principal opportunity appears to be increased profitability from reduced costs. In both cases reduced operating costs from the introduction of a dry, low cost waste rejection process result directly in a lower economic cutoff for the resource, thereby maximizing the conversion of resource material to finished metal. A study concerning a small, high grade mine is presented in the paper as a case in point.

III. KEUMSEONG MINE: A CASE STUDY

The Keumseong molybdenum mine is located approximately 8 km south of Jecheon, and approximately 130 km southeast of the capital Seoul. The Keumseong molybdenum deposits were discovered in 1966 by the state geological institute. The ore is of a molybdenum calc- skarn-type that has been developed in the contact zone between calcareous sediments of the Choseon Group and nearby intrusive rocks. The orezone occurs at shallow depth and extends some 800 m in strike length and between 80 and 100 m along dip. The skarn mineralization is subdivided into two types; a banded clinopyroxene skarn and a massive clinopyroxene-garnet skarn. The ore minerals are molybdenite with lesser amounts of pyrrhotite, pyrite and scheelite. Molybdenite occurs as small masses, stringers and flakes disseminated within the clinopyroxene-garnet skarn although semi- to massive molybdenite was commonly

[1] www.commodas-ultrasort.com/products

observed. A historic 'reserve estimate'[2] was reported and based on surface and underground geological surveys and diamond drilling, suggesting approximately 35 Mt of potentially economic material at the site, grading on average 0.09% Mo.

Mining methods are generally planned around sublevel stoping, with shrinkage stoping used at the uppermost levels of the operation where a sill pillar needs to be retained between the workings and the surface. The current mine plan calls for a daily throughput of 1000 tpd of ore with a head grade of 0.3% MoS_2 over a 300-day working year.

A. Milling

Treatment is by primary crushing underground, hoisting by conveyor followed by grinding and flotation designed to produce a single molybdenite concentrate which is sold to domestic smelters for further processing and refining (Figure 3).

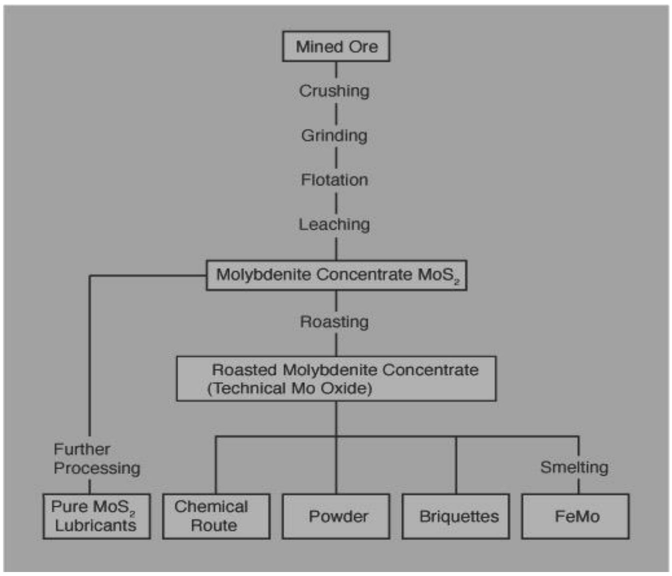

Figure 3 - Kuemseong General Molybdenite Processing Flowsheet

The project itself benefits from a high Mo grade, with improved Mo grades over those usually expected.

B. Project Economics

Information concerning the project was input into the MineSense 'PreCalculatOre' project evaluation software. Table 2 shows the assumptions used.

Table 2 – Assumptions for Economic Evaluation of the Kuemseung Mine

Assumption	Value
Total Concentrate Production	**749 tonnes per year**
Pounds of Saleable MoS_2	**1.65 million per year**
Price per pound	**US$25**
Mining and Processing Cost	**US$8.50 per pound saleable**
TC/RC	**US$0.50 per pound saleable**
Capital Cost (Mine and Mill)	**US$17 million**
Corporate Tax Rate	**28%**
Mine Life	**10 years**
Discount Rate	**10%**

[2] The reserve estimate was offered by the company. These figures are not NI 43-101 compliant, nor have they been verified, vetted, audited or confirmed in any way and therefore should be used as an informal guide and not relied upon for any investment decision.

Based on the assumptions above, the project analysis yielded the following results (Figure 4):

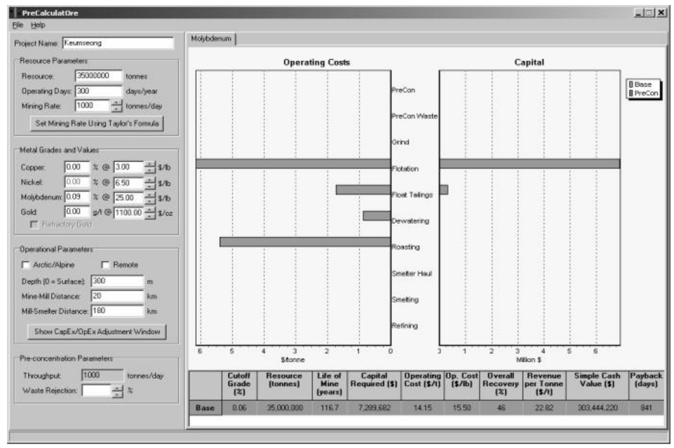

Figure 4 - Economic Base Case, Kuemseung Mine

Based on the assumptions used, the project appears quite robust. However, high unit operating costs mean that Mo prices below $19/lb are not economic, and topographic constraints on tailings disposal significantly limit mine life for the given capital expenditure.

C. Testwork

In order to evaluate pre-concentration potential, four different separation techniques, including optical separation, dense medium separation, x-ray fluorescence and conductivity separation, were tested. The study was specifically designed to identify the physical impacts, and resulting financial benefits of pre-concentration by:

1. Assessing the most economical and practical pre-concentration method for the operation;
2. Determining the implications of integrating a pre-concentration method into Keumsung's current process flowsheet;
3. Assessing impacts on operating cost and Mo recovery at the mine and translating these impacts into economic terms.

The work program consisted of:

- Sampling of ore from the Kuemseong Mine
- Crushing the feed sample to an 80% passing 1 inch

- Screening the undersize to -1 inch, + ¾ inch
- Riffling into 4 sub-samples for the pre-concentration testing
- Testing of optical, x-ray, density and conductivity separation methods on the sub-samples
- Evaluating impacts on process economics based on pre-concentrate characteristics produced

A 30kg sample of Kuemseong ore was obtained and prepared by crushing in advance of the pre-concentration tests (Figure 5).

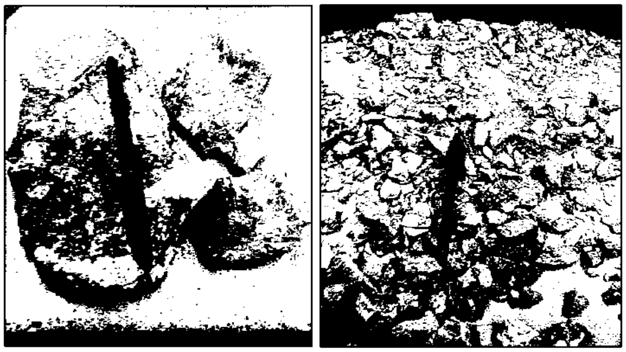

Figure 5 – Mo Ore Sample from Keumseong Mine, South Korea

After the pre-concentration tests were completed, waste and concentrate products were weighed and ground to 100% passing 100 microns and sent for assay.

D. *Optical Separation*

Optical separation was accomplished by visually separating the samples into concentrate and reject based on the visible concentration of molybdenite in the grains. Each sample was classified to either concentrate or reject using the Compton schema as a guideline. Rejects were eliminated based on the Compton's mineral concentration schema of less than 5% mineralization. The total number of grains and total weight in each category was recorded before submitting the sample for assay.

1) *X-Ray Flourescence (XRF)*

An Innov-X Systems α-600 dual energy handheld X-ray fluorescent analyser was used to measure the molybdenum and sulphide concentration in each of the grains in sample number 2. A 4-spot analysis procedure was used which gives consistent and high correlation results to assay [13]. The grains were numbered and classified into three concentration groups based on their molybdenum concentration: high, intermediate, and low. As with the optical testwork, the total number of grains in each group, the total weight of each group and assay results were recorded.

2) *Density Medium Separation (DMS)*

One of the Kuemseong sub-samples was subjected to heavy liquid separation (HLS) in a methylene iodide / bromide solution at SG 3.0 and 3.2. The mass of the three separation products at SG +3.2, -3.2 +3.0 and -3.0 were taken, dried, then ground to 100% passing 100 micron and submitted for assay.

3) *Conductivity*

To evaluate conductivity in the grains, the sample was scanned with the MineSense 'B2' desktop high frequency electromagnetic (HFEMS) analyser (Figure 6). The B2 scanner delivers magnitude (conductivity) and phase (magnetic susceptibility) results over a range of scanning frequencies from 0-1400kHz. Sine wave, square wave (with harmonics) and triangular wave excitation is possible. However, measured conductivity and magnetic susceptibility of the Kuemseung sample was below the threshold of the technique and further testing with the method was abandoned.

Figure 6 – MineSense 'B2' HFEMS Analyser

4) *Results*

Results of the molybdenum pre-concentration testing are presented in Table 4.

Table 4 – Metallurgical Results – Kuemseong Mine

Method	Criteria	Weight (%)	Assay (%)		Recovery (%)
			Mo	S	Mo
Optical					
Concentrate	>10% mineral	61.6	0.239	2.00	95.3
Tails	<10% mineral	38.4	0.019	0.25	4.7
Head		100	0.155	1.33	100.0
XRF					
Concentrate	25,000 - 50,000ppm	15.5	0.685	5.56	45.8
Intermediate	4,000 - 25,000ppm	39.8	0.212	1.96	36.4
Tails	500 – 25,000ppm	44.7	0.092	0.93	17.7
Head	23,200ppm	100	0.232	2.06	100.0
DMS					
Concentrate	>3.2 SG	11.4	0.132	1.04	13.5
Intermediate	-3.2 +3.0 SG	47.9	0.097	1.06	41.8
Tails	<3.0 SG	40.7	0.122	1.14	44.7
Head		100%	0.111	1.09	100.0

International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-2, Issue-5, May 2015

E. Discussion of Upgrading Test Results

Poor results were recorded for two of the four pre-concentration methods tested. No discernible correlation of conductivity with Mo concentration was determined for the sample. Investigation of the negative result suggests as Mo has an incomplete 'd' electron sub-shell that tends to store any excess electrons from chemical or electrical activities thus producing a stable valence. Pre-sorting molybdenum ores by using differences in electrical conductivity is therefore considered to have little to no application on this basis. Density separation results were poor on account of poor density differentials between the grains in the test. Inversion of grade in the -3.2+3.0SG and -3.0 SG material was also observed confirming poor separation potential by density. It is suggested that grade differentials of 0.01%Mo are insufficient to generate sufficiently high concentration criteria between the grains and separation by density is therefore not indicated. However, results for separation by optical and x-ray fluorescent methods were excellent. Using optical methods a pre-concentrate 62.2% by mass grading 0.239%Mo was produced at a Mo recovery of 95.3%. Using X-ray fluorescent methods a pre-concentrate 55.3% by mass grading 0.347% Mo was produced at a Mo recovery of 82.3%. The high grade in tails is likely caused by a higher feed grade observed in the test.

IV. Economic Modeling

Computer modelling was undertaken to test the economic feasibility of the pre-concentration methods tested on the Keumseong ore using the Pre-CalculatOre software package. Pre-CalculatOre is a techno-economic modelling package jointly developed by MineSense and Xstrata Process Support of Sudbury Ontario (www.minesense.com/precalculatore.html). Pre-CalculatOre combines process and cost models for mining, transportation, milling, smelting and refining stages based on empirical data from operating mines to predict outcomes of pre-concentration on operating cost and metal recoveries, hence impacts on cutoff grades and resource recovery. Valid flowsheets based on real operating data have been developed for copper, nickel, molybdenum and gold, which, combined with pre-concentration data from the testwork can be used to compare operating cost and recovery on an incremental basis for the same operation. Using Pre-CalculatOre the XRF option can be tested against the base case, the optical technology can be tested against the base case and the optical technology against the XRF technology. The assumptions used in the analysis are shown on Table 4.

The plant feed recovery is the feed rate after pre-concentration; the head grade improvement indicates improvement over the base case mill feed grade, and the recovery stated is the recovery of Molybdenum during pre-concentration only. A recovery of 98% must be for the existing process must be applied as well in determining the metal recovery in the process. The resulting mass and metal balance was used to calculate the amount of Mo that is available for sale in each scenario - base case, XRF pre-concentration and optical pre-concentration - to determine the total revenue. Total plant operating cost is calculated on the tonnage of feed after pre-concentration in each case. It is assumed that the capital is spent at the beginning of year 1. All project options can then be compared on an equal basis. All other project evaluation assumptions are the same as in Table 2.

Table 4 - Model Input Assumptions

Assumptions	
Mill operating cost ($/t)	14.15
Pre-concentration plant capital Cost ($million)	$20M
Waste rejection	40%
Sorting recovery	95%
Grade improvement	38%
Pre-concentration operating cost	$3.20/t
Tax rate	30%
Amortization rate	10 year, straight line

A. Results

The base case Evaluation using PreCalculatOre indicates positive economic impact of the sorting strategy over the base case (Figure 7).

Figure 7 – Pre-concentration Economic Evaluation, Keumseung Mine

According to the evaluation, operating costs are reduced by $3.29/t, Mo recovery improves by 2%, economic cutoff is reduced from 0.06% Mo to 0.04% Mo and the amount of potentially economic material in the resource is increased from 35Mt to 41Mt. Total undiscounted cash value of the property is increased from $300M to $525M over the life of mine.

In order to be sure that the incremental results were robust across a variation in the value of the important input parameters, a further sensitivity evaluation was performed for key assumptions and results. Values for the degree of waste rejection, head grade increase achieved, and overall Mo recovery were allowed to vary between 50% and 150% of the nominal values calculated in the study. The results of the sensitivity analysis for the optical pre-concentration scenario are presented in Figure 8.

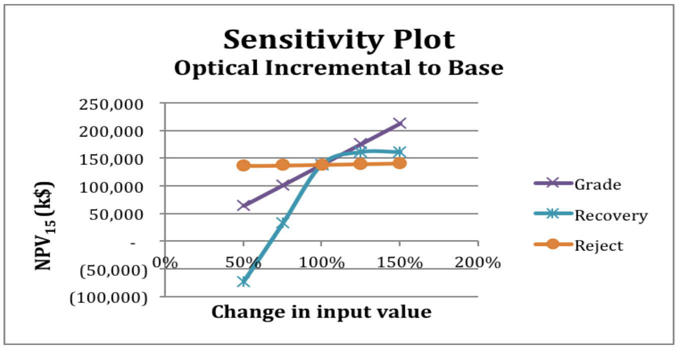

Figure 8 – Sensitivity Analysis of Key Parameters

As suggested, ore pre-concentration has great potential in lowering mass handling by means of early waste elimination, which significantly reduces grinding requirements, reduced operating necessities such as reagents, water and electricity, and also increases the mill feed grade. Tailings impoundment restrictions are also accordingly reduced. Financially, the method of pre-concentration increases the mine-ability of more marginal reserves with the quick generation of cashflow with significant production enhancement for a comparably small capital outlay. The results are also robust, showing strong returns within ±10% of assumed parameters.

V. Summary and Conclusions

Based on the testwork and ensuing economic analysis using the PreCalculatOre tool it is clear that there is a very strong argument for further investigation of pre-concentration of Keumseong ore at the scoping- or pre-feasibility study level, to confirm the efficacy of pre-concentration to lower costs and increase production at Keumseong Mine. From this work, a number of specific and general conclusions can be drawn:

Specific conclusions:

- Of the 4 pre-concentration technologies tested, XRF and optical sorting technologies produced results meriting further work
- Dense media separation and electrical conductivity testwork suggests that these strategies are not appropriate for this particular ore type
- Pre-concentration of the Keumseung ore produces mill feed grade improvements while reducing the amount of waste material that would otherwise be milled, and reduces tailings production from the Keumseung mill.
- The mass balance improvements at the noted metal recoveries yield significant cost benefits at relatively low capital cost to the mine, significantly improving mine economics
- There may be other operating strategies that could further improve the mass balance characteristics of this mine, such as increasing mining rate together with pre-concentration of the mined ore to increase mill metal producing capacity, an option which can be modelled in the next phase of work.

General conclusions:

- Advances in sensor design and sorting flowsheet design now allows a wide range of physical, electrical and magnetic characteristics of ore materials to be exploited for early separation of waste in a relatively inexpensive pre-sorting stage at the mine
- Pre-concentration of mill feed ores have the potential to dramatically improve mine economics while reducing environmental footprints by increasing the feed grade and reducing the amount of waste material that would otherwise require energy intensive comminution
- Pre-concentration methodologies will likely have the greatest impact on smaller mines with more controllable mill feed streams at least until technologies improve to handle high mass flows and low grade ores
- Pre-concentration technologies have the potential to increase resource conversion by providing for low energy, low cost waste rejection with high recoveries and low water requirements, thereby reducing the cut-off grade required for the production of economic mill feed

References

[1] Bamber, A.S., (2008) Integrated Mining and Processing Systems for the Increased Sustainability of Hard Rock Mining, UBC Ph.D. Thesis, April 2008.

[2] Kelly, E.G. and D.J. Spottiswood, (1995) *Introduction to Mineral Processing*. Australian Mineral Foundation, Adelaide, South Australia.

[3] Collins, D.N., and C.F. Bonney, (1995) The Separation of Coarse Particles (>1mm) Using Sorting Methods Based on Optical, Electrical Gravity and Magnetic Processes, *MIRO Technical ReviewSeries #18*, MIRO.

[4] Goode, J., (2006) Ore Sorter to Shake Up Nickel Production, *Australian Paydirt*, p 8, June 8.

[5] Kinver, P., (2002) Anglo Platinum's Western Bushveld Operations, *Anglo Platinum Annual Facility Visit Presentation*, March 2002.

[6] LionOre, (2006) Selkirk Scoping Study Indicates Potential for a Large New Nickel Deposit at Tati Nickel, *LionOre International Press Release*, SEDAR Ref 00000589E, 6 March 2006.

[7] Bamber, A.S., and D. Houlahan, (2007) Initial 'B2' Report, *BC Mining Research Internal Report*, November 2007.

[8] Cutmore, N.G., Liu, Y., and A.G. Middleton (1998) On-line ore charactisation and sorting. *Minerals Engineering*. Volume 11, Issue 9, pp. 843-847.

[9] Lane, G.R., C. Martin, and E. Pirard, (2008) Techniques and applications for predictive metallurgy and pre characterization using optical image analysis. *Minerals Engineering*. Volume 21, Issue 7, pp. 568-577.

[10] Pirard, E. (2004) Microspectral imaging of ore minerals in optical mineralogy. *Mineralogical Magazine*, 66 (2), pp. 323-333.

[11] Kattentidt, H.U.R., T.P.R. de Jong and W.L. Dalmijn (2003) Multisensor identification and sorting of bulk solids. *Control Engineering Practice*. Volume 11, Issue 1, pp. 41-47.

[12] Salter, J.D., Wyatt, N.P.G., 1991, Sorting in the Minerals Industry: Past, Present and Future, *Minerals Engineering*, Vol 4, No 7-11 pp 779-796, 1991.

[13] Khoshaba, B. (2010) Procedure for Service Testing of Metal Ores with the B2 and Handheld XRF Analyzer, *MineSense Technologies Standard Lab Procedure* October 2010.

Dr. Michael Hitch H.Dipl. (Geo. Eng.), B.S. (Geo.), M.Sc. (Geo), Ph.D. (Env Stud.), P.Geo., P.Eng. is Associate Professor at the Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver Canada. Dr. Hitch's research interests centre on the mine of the future. This notion challenges one to consider not only the traditional aspects of mine design, extraction and closure but also aspects of greenhouse gas emissions and the social implications of mine operation. Dr. Hitch's research considers operational efficiencies through the lens of sustainability and appropriate extraction that seeks to provide a platform for local prosperity and sustainable livelihoods. Dr. Hitch has travelled to 184 countries in various capacities including as a senior mining executive in his prior life. His focus continues to be on the development of 'human-scale' mining operations that can improve the biophysical integrity, economic sufficiency and the social wellbeing of the environments within which we operate.

Dr. Andrew Bamber B.Sc. (Mech.), Ph.D. (Mining), P.Eng. is a mechanical, process and mining engineer with over 15 years' experience in mining projects and operations in Southern Africa, Kazakhstan and Canada. Andrew has extensive experience in process development, as well as process equipment design and manufacture. Andrew has contributed as Lead Engineer to several mining projects, as well as numerous scoping, pre-feasibility, feasibility and technical studies. Previous projects include the Nyala Alumina Project for Rhino Minerals, the Dwarsrivier Chrome Project for Associated Manganese Mines of SA, the Mimosa Platinum Phase III expansion for Aquarius, and the Voskhod Chrome Project for Oriel Resources. In 1999 he created a multi-disciplinary consultancy Sherliker Design and Engineering, together with his partner, Brian Cameron, and while a post-graduate student at UBC co-founded BC Mining Research Limited, now a UBC-affiliated company. Since founding MineSense in 2008, his role has involved research, prototype design, development and testing, application development, as well as business development, operations and financing.

Patricia Oka B.A.Sc. (Mining) is a graduate student at the Department of Civil Engineering, University of British Columbia, Vancouver, Canada.