Ore Sorting

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ABSTRACT: While manual ore sorting has been reported since the beginning of mining history, significant advances have been made recently in various sensing technologies in recent years. As the equipment/systems relative costs are reduced, machine sorters are showing an increased impact on the mining industry, specifically in areas such as uranium and magnesite processing. This paper reviews the initial adaptation of food sorters to optical ore sorters, specific radiometric sensing sorters for uranium ores to the modern photometric, and several sensing technologies based sorters.

INTRODUCTION

Ore sorting is typically used for three purposes:

1. Preconcentration, primarily of low-grade ores
2. Producing final quality material
3. Sorting a feed into a high-grade and a low-grade product

By rejecting waste grade material at low overall cost, an ore may be upgraded to a degree that makes it profitable (Arvidson 1987). In some cases, the waste may even contain a detrimental component, which by its elimination, makes subsequent processing possible (Bibby 1982).

The final quality material may be for direct sale or for use in a downstream process, such as grinding for filler/powder, or calcination/fusion/smelting.

The third type of application is intended for materials where there may be no waste or relatively little waste to be rejected resulting in two valuable products which may then proceed to different downstream processing lines. Advancing technologies are likely to increase the use of this application.

A large range of sensing technologies and fast complex computations capabilities continue to be developed and will be mentioned in the emerging technologies section. New ore sorting possibilities are being continuously developed.

HISTORY

In the 1940s, food sorters came on the market. These were based on optical recognition technologies. It was soon realized that machine sorters could also be used for ores. By making some models more robust, modified peanut and grape sorters were applied to rock salt and talc sorting. One of the first large installations was for magnesite ore sorting in Greece. Diamond sorters were also developed, first using optical methods. However, since the global food sorting market grew very rapidly, the main focus of development was in that area rather than for ores.

Special sorters for diamonds using their x-ray fluorescence property (and in some situations luminescence often induced by ultraviolet light) soon overtook manual sorting and became an industry standard method. After preconcentration by heavy media density separation, sorters processing wet material upgraded products prior to drying and final automated dry sorting. Color sorting of the diamonds was done manually.

The development of uranium ore sorters began with the first machines installed at the Mary Kathleen mine in 1960 and later upgraded with high-capacity sorters in 1979. Several such machines were used to upgrade uranium ores, which otherwise would have been uneconomical. Several radiometric sorters were also used for gold ores in South Africa. Uranium associated with gold was used as a "handle" to recover the gold values.

Photometric sorters using a fast scanning laser beam were first used for gold ores in South Africa in 1972 (Kidd 1983). Such high-capacity machines changed the magnesite ore industry in Greece and were later used also in the Australian magnesite ore processing plants. The sorters were useful in several different but fairly unique applications such as some gold ores, limestone, phosphate, wolframite and other valuable minerals in quartz, talc and spodumene ores. One large installation was for lignite coal in Hungary.

Accelerating computer development in the 1990s resulted in possibilities for fast processing of huge, complex data sets at rapidly decreased cost making more expensive, dedicated hardwired processing technologies too costly. New developments resulted in less expensive machines that are more economical to use in an increasing number of ore sorting situations. Various sensors became more reliable and new waste recycling technologies were being adapted to ore sorting applications.

FIRST APPLICATIONS OF AUTOMATED ORE SORTING

The first optical sorters were intended to replace human labor to sort discrete particles that had distinct visible differences (Arvidson 2002). Material was fed in channels where each particle was seen by a scanning device to detect optical differences (light vs. dark), the signal over or under a threshold value fed to the mechanism that would kick the fast-moving particle out of the natural trajectory. Both mechanical plungers or flaps and air jets were used, the latter type dominating.

High-capacity optical sorters using a fast-scanning laser beam were purpose designed and constructed for heavy duty ore sorting (Schapper 1977). No longer was it necessary to feed the size fractions through channels. Each particle was tracked on a fast moving (4 m/s) belt and those determined to be satisfying criteria for ejection were accurately sized and located for a precisely tuned air blast. The fast processors were hard-wired, allowing moderate flexibility of the photometric parameter settings.

Although the first generations of advanced optical ore sorters could not come close to the capability of the human eye and brain to recognize subtle nuances in color, shape, and contrast within a particle, they were successful in many applications, most notably in sorting magnesite ore at the Fimisco operation in Greece. As the magnesite is brightly white and the unwanted material, mainly serpentine in large veins, is brown to black, sorting based on reflectivity was relatively easy.

When laser sorters became available, they were quickly accepted by the South African gold industry and further developed within the Greek magnesite industry. A pioneering large installation for the magnesite ores of Grecian Magnesite was implemented in 1977 and has been in full production to this day. This installation utilizes 11 laser sorters and has recently installed 5 line-scan camera sorters for fine sized material. There are other laser sorter installations, such as the 4 sorters at the Oroszlany mine in Hungary, but most consist of fewer units.

Radiometric sorter pioneering company Mary Kathleen Uranium Ltd operated over short time periods, first 1958 to 1963 and then 1976 to 1982. In both periods, radiometric sorters played an important role separating the highly acid consuming calcite waste from the uranium product.

One of the earliest radiometric sorter machines was used for many decades at the Schwartzwalder uranium mine until its closure in 1995. Energy Fuels used a late model for a mine operation in Arizona with great success. A coarse size fraction was upgraded substantially while rejecting low-grade waste thereby eliminating shipping costs to a remote process plant in Utah. Nearly 30 radiometric sorters were in operation at one time, recovering uranium minerals and some also gold as mentioned in the prior section.

INDUSTRY IMPACT IN THE 20TH CENTURY

Ore sorting was generally an uncommon technology in the mining industry before the 21st century. Several reasons for this are suggested.

- Ore sorting is generally best used in preconcentration applications, the most logical position is in the earliest part of processing, i.e., after crushing of run-of-mine ore or sometimes after secondary crushing. The issues are
  a. The technical responsibility area before the ore was fed into a process plant was typically related to mining. Ore sorting technology was generally unknown to mining engineers.
  b. If a process plant did not have secondary crushing, only primary followed by SAG (Semi-Autogenous Grinding), there was often poor economy to retrofit such an operation with additional crushing, washing, screening, conveying.
  c. Mining schools did not teach ore sorting to a significant level if at all within their mineral processing curricula. Hence, little information about sorting was available also to mineral processing professionals.
- Ore sorting coarse rock may cause a recovery reduction of the valuable mineral(s), even slightly. Hence, it was frequently thought that the overall recovery would be reduced. That was a false perception in many cases, but remained an obstacle for more in-depth investigations. It was shown in some cases, that the more uniform and higher feed grade for downstream processing could improve processing recovery compared to not sorted feed, ultimately improving overall recovery or often maintaining that same level at reduced overall cost.
- Most advanced ore sorting technologies were owned by a single large mining company for a long period of time. A former company manager stated that it was never their intent to make the ore sorting subsidiary a profitable business, but rather to secure that the technologies remained available within the group of companies.
- For some intended technology developments, sensor reliability was a great challenge. In initial commercial attempts, it was a requirement to have highly skilled operators and very stable power supplies which was not possible in some countries.

Nevertheless, ore sorting was very important in the cases where it was applied and highly profitable for the companies using them.

TECHNOLOGY DEVELOPMENTS

In the mid-80s, recycling of household waste was moving ahead in Europe, especially in Germany, encouraged by a new legal framework. It was no longer permitted to dump waste, and it was difficult to burn waste with a content of glass, metals, paper, cardboard or plastics. Hundreds of new recycling plants had to be built, and most of them worked by handpicking only. Productivity was low, labor costs were high, and the working conditions were not seen as acceptable for developed countries.

Contrary to the minerals industry, the recycling industry at that time was dominated by small and medium sized enterprises, owned by entrepreneurs comfortable making fast and sometimes risky decisions. Spin-offs from universities and other research institutions in the field of computer technology became available. Image processing was popular, which soon was applied to the emerging recycling industry. There was no "traditional" technology established and the recycling industry was free to choose new standards and eager to adapt technology. Computing power increased dramatically and new concepts of computer based data processing and sorting algorithms were developed. This led to the introduction of advanced sensor based sorting, first mainly optical sorting (with line scan cameras) and inductive sensors (metal detectors) in industrial recycling in a short period of time.

After technologies were improved and refined, they became useful for the ore processing industry. The prior arguments against employing them; not the right sensors available, low throughput, too complicated, too delicate, no skilled personal, etc. were all reduced or eliminated by the thousands of applications in the recycling industry. Hence, the exploitation of improved technologies was a natural consequence and is now an expanding technology area within the minerals industry.

Basics and Systems

Sensor-based sorting is a combination of a detection by a sensor and an ejection of single particles. Like hand-picking, the ejection or acceptance of a particle is based on a yes/no decision, which is generated by the evaluation of acquired data through a sorting algorithm. In other separation and concentration methods, the force, which moves, holds or deflects the particle, is directly coupled to the physical characteristics, such as magnetic properties or density. In sensor based sorting, physical property and separation action are not directly linked. The measurement of one or more properties takes place, after which it is decided by data processing, if the property characterizes the particle as to "eject" or to "accept." The whole system of sensor based sorting comprises of four sub-processes:

1. Feed preparation
2. Material presentation
3. Detection and evaluation
4. Ejection

Feed Preparation

Feed preparation is needed to ensure a condition of the feed material suitable for the chosen sensor and machine type. This includes screening to produce a narrow particle size distribution, and a treatment of the particle surface by de-dusting, scrubbing, washing, de-watering and/or drying. Few sensors need additional feed preparation processes. Sortable particle sizes are influenced by the spatial resolution of the particulate sensor and by necessary degree of liberation. Currently, material

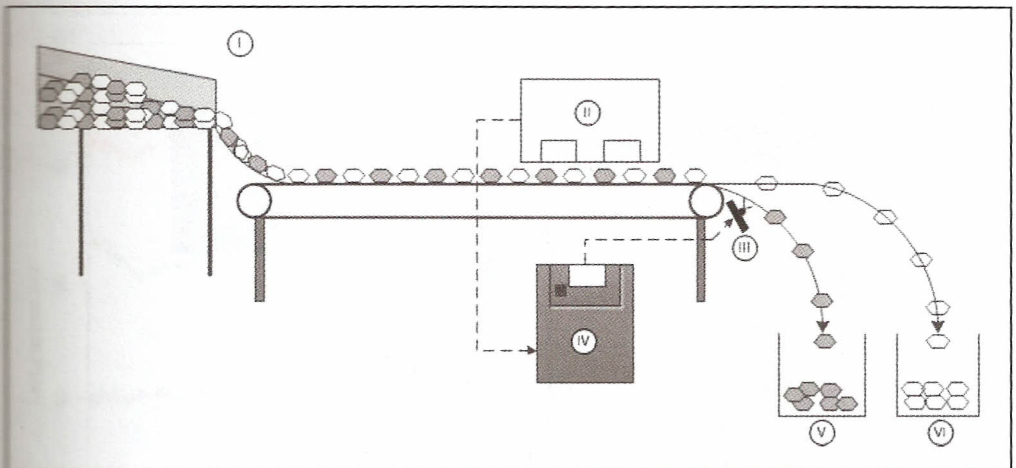

Figure 1. Belt-type sorter: (I) material presentation by vibrating feeder and belt, (II) sensors, (III) ejection nozzle array, (IV) CPU, (V & VI) accepted and ejected products, respectively

from 1 mm to about 300 mm (12") can be processed on a sensor based sorter. As the technology works with a single-particle layer feed, and the number of single particles which can be detected, evaluated, and ejected per time unit is limited, particle size has a major impact on throughput. At maximum particle sizes, a throughput of up to 300 ton per meter sorter width per hour is possible, but at particle sizes of a few millimeters, only a few tons per hour on the same machine width can be treated.

Material Presentation

The particles must be presented to the sensor(s) as single particles, accomplished by spreading and accelerating them along two or more conveying steps. For some sensors and detection modes, it is necessary to isolate each particle from its neighbors (single particle mode), which reduces the covering of the available space and decreases throughput. The particles have to follow defined paths between detection point and ejection point to avoid misplacement. For material presentation, the two basic current sorter machine types use either a vibrating feeder followed by a fast conveyor belt (belt-type sorter) or a vibrating chute followed by a sliding chute (chute-type sorter), see Figures 1 and 2.

Detection and Evaluation

The detection of material properties of minerals and ores can be made along the whole electromagnetic spectrum, see Figure 3. Not all possible wave lengths are employed in industrial scale yet.

Sensors can be classified into a few main groups:

1. Sensors for the detection of surface properties
2. Sensors for the detection of properties representing the whole particle
3. Sensors to detect secondary material properties like color, reflectivity, brightness, conductivity, density, magnetic susceptibility, gamma ray emission
4. Sensors for the detection of primary material properties such as elemental or mineralogical composition

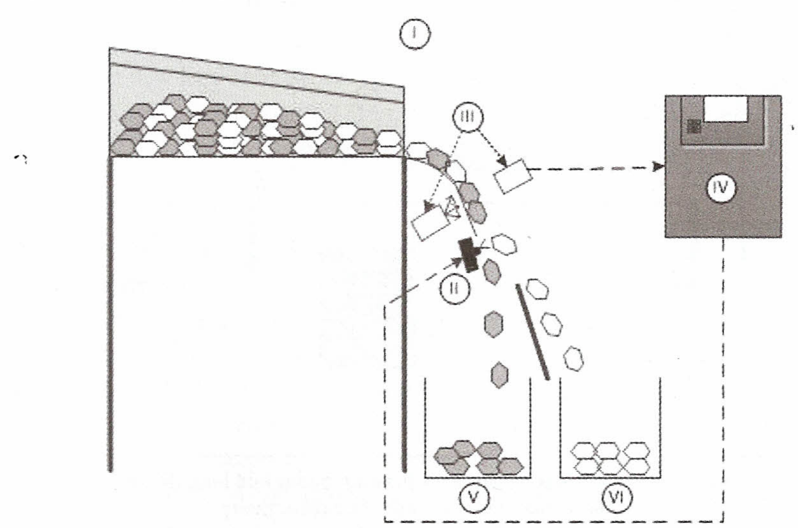

Figure 2. Chute-type sorter: (I) material presentation by vibrating feeder and sliding chute, (II) sensors, (III) ejection nozzle array, (IV) CPU, (V & VI) accepted and ejected products, respectively

	[m]
Gamma-radiation	10^{-12}
	10^{-11}
X-ray	10^{-10}
	10^{-9}
	10^{-8}
Ultraviolett (UV)	10^{-7}
Visible light (VIS)	10^{-6}
Near Infrared (NIR)	10^{-5}
	10^{-4}
Infrared (IR)	10^{-3}
Microwaves	10^{-2}
	10^{-1}
	10^{1}
Radio Waves	10^{2}
	10^{3}
Alternating Current (AC)	10^{4}

Sensor/Technology	Material Property	Sorter application
RM (Radiometric)	Natural Gamma Radiation	Radioactive Ores
XRT (X-ray Transmission)	Atomic Density	Base and Heavy Metal Ores Precious Metal Ores Industrial Minerals, Coal, Diamonds, Scrap Metals
XRF	Visible Fluorescence under X-rays	Diamonds
COLOR (CCD Color Camera)	Reflection, Absorption, Transmission	Base Metal Ores Precious Metal Ores Industrial Minerals Diamonds, Glass
PM (Photometric)	Monochromatic Reflection/Absorption	Industrial Minerals Precious Stones Diamonds
NIR (Near Infrared Spectrometry)	Reflection, Absorption	Base Metal Ores Industrial Minerals Plastic Paper, Cardboard
IR (Infrared Camera)	Heat conductivity, heat *dissipation*	Base Metal Sulphide Ores Precious Metal Ores *Industrial Minerals* Graphite, Coal
EM (Electro-Magnetic Sensor)	Conductivity, Permeability	Base Metal Sulphide Ores Scrap metals

Figure 3. Sensors along the electromagnetic spectrum (Wotruba 2011)

Until recently, all properties which could be detected were "secondary"; properties like color, transparency, brightness, conductivity etc. These are not specific for a certain mineral or grade as there are minerals which can be found in a variety of colors, but a certain degree of conductivity can be related to various sulfides. For some applications, the detection of secondary properties is not sufficient.

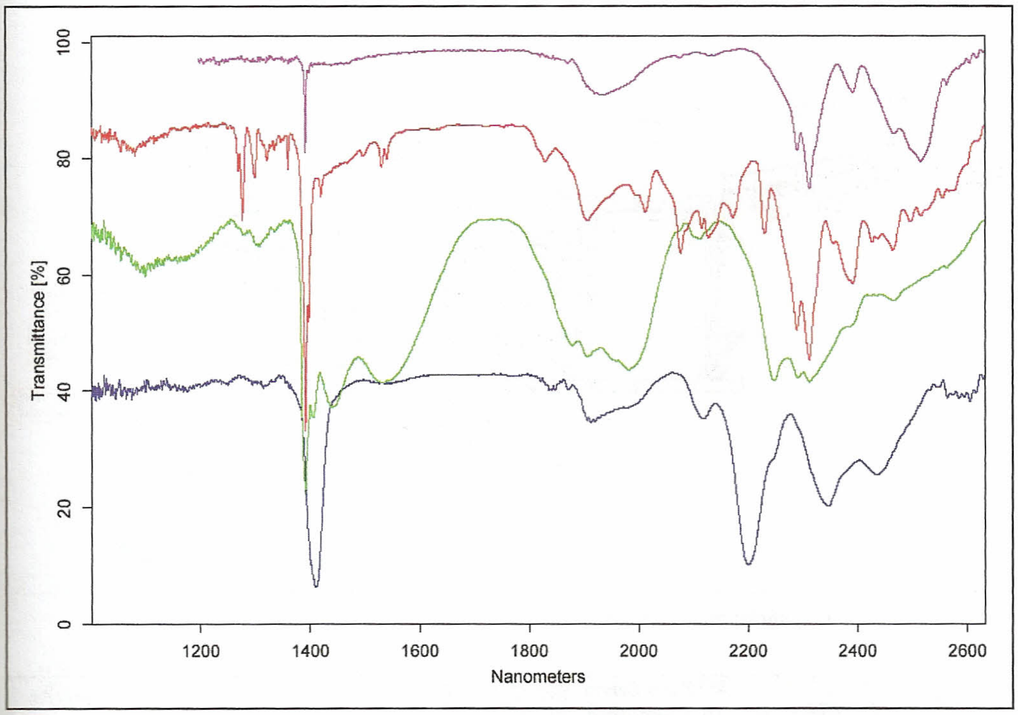

Figure 4. NIR-Spectra of milky quartz (blue), calcite (pink), talc (red), and chlorite (green)

There are sensors, which are able to detect "primary" properties like absorption of distinct wavelengths in the near-infrared (NIR)-spectrum or conduct direct elemental analyses by a XRF (x-ray fluorescence) sensor. With a NIR-sensor, NIR-active minerals can be identified selectively. This technology was used for decades in geological exploration. A NIR-Sorter of the most recent generation can scan and evaluate several hundred thousand NIR-spectra per second. With this sorter type, it is for example possible to distinguish between white quartz, calcite and talc, see Figure 4 (Robben 2011).

An electromagnetic machine sorting principle is shown in Figure 5. An example of elemental composition sorting is shown in Figure 6. Note that reproduction in black and white does not permit full justice to these illustrations.

The following sensors are currently applied in industrial scale (numbers within brackets refer to the sensor types listed above):

- Optical (line-scan camera; monochromatic laser scanner) (I, II)
- NIR (near-infrared spectroscopy) (I, IV)
- XRT (x-ray transmission (II, III)
- Inductive (II, III)
- XRF (x-ray fluorescence with photo-multiplier (for diamonds) (I, III)
- XRF (x-ray fluorescence for elemental analysis (I, IV)
- Radiometric sensor (gamma-ray spectrometer, scintillometer) (II, III, IV)

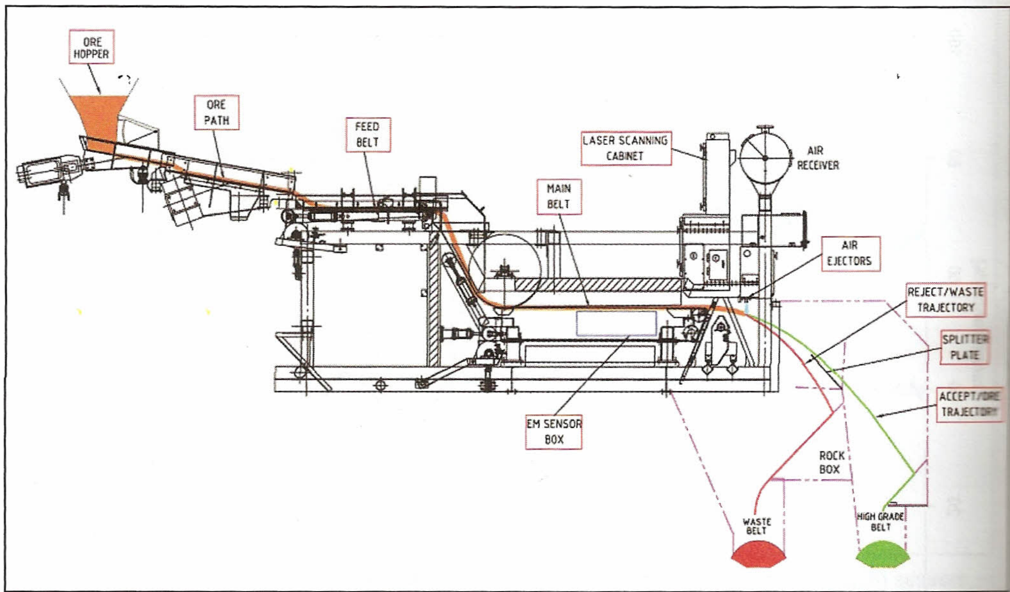

Figure 5. Principle of a sorter machine based on EM sensing

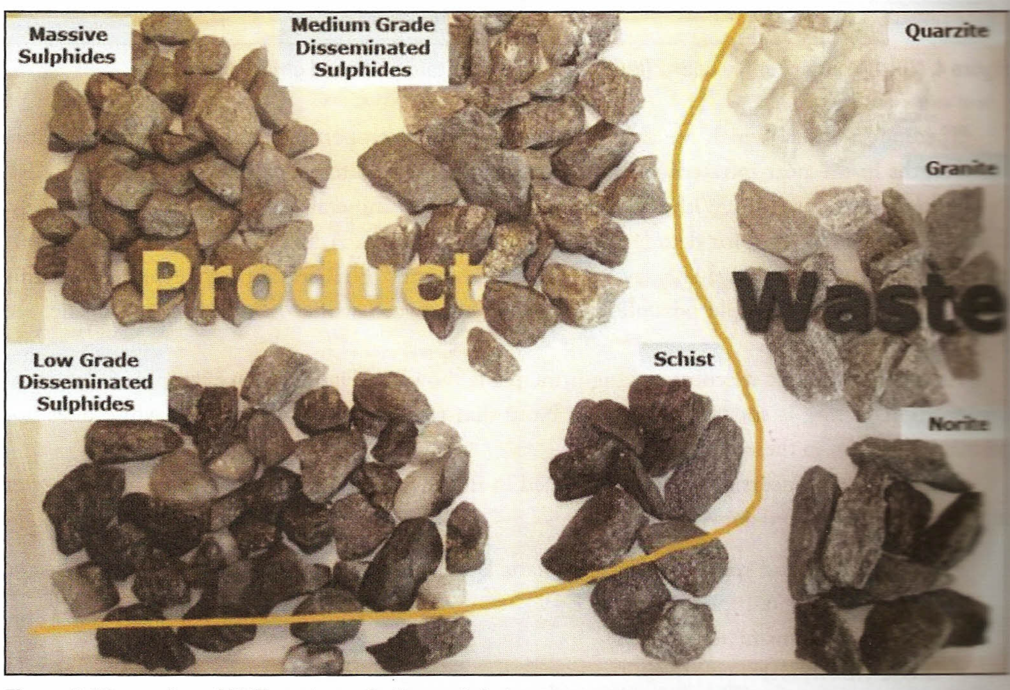

Figure 6. Illustration of XRT sorting—Sudbury nickel ore

Currently known applications in the minerals industry:

1. Optical Sensors (line scan cameras)
   a. Industrial minerals (calcite/limestone, dolomite, quartz, feldspar, talc, rock salt, etc.)
   b. Precious stones (diamonds, emeralds, tanzanite)
   c. Metal ores (chrome, gold, nickel, platinum, copper)
2. NIR
   a. Talc
   b. Colemanite (boron ore)
   c. Limestone
3. XRT
   a. Scheelite, wolframite
   b. Coal
   c. Diamonds
   d. Iron ore
4. Inductive
   a. Sulfide ores (nickel, copper, etc.)
5. XRF with photomultiplier
   a. Diamonds
6. XRF (elemental analysis)
   a. Sulfide ores (nickel, copper, zinc)
   b. Precious metals (gold, platinum)
   c. Chromite
   d. Manganese
   e. Iron ore
7. Radiometric
   a. Uranium ores
8. Monochromatic Laser Reflection
   a. Magnesite
   b. Limestone
   c. Talc

Sensors in laboratory, prototype and pilot scale (numbers within brackets refer to the sensor types listed above):

- Optical spectral resolution sensors (I, III)
- Sensors for fluorescent minerals (optical, with spectral resolution, laser induced) (I, III)
- Microwave excitation in combination with thermal infrared sensor (II, III)
- Rahman-spectroscopy-sensor (I, IV)
- Terahertz-transmission (II, III)
- LIBS (Laser Induced Breakdown Spectrometry). There is already in commercial uses for fast on-belt analysis of several elements, including such light ones as Ca and Mg. Hence, this technology may be adapted for ore particle sorting.

Ejection Methods

Ejection is either done by air jets from arrays of high-speed compressed air valves or electrically, pneumatically, or hydraulically driven flaps or plungers. Water valve system were abandoned very early. It is also possible to conduct bulk-sorting of a whole material stream by conveyor-flaps/ dividers or reversible conveyors.

Summary of Possible Ore Sorter Applications (Examples)

Contrary to classical separation technologies for coarse sizes such as density separation or magnetic separation (e.g., for iron ores), sensor based sorters can separate particles with very small differences in their properties. This enables a range of applications:

- Waste elimination or pre-concentration before further milling and concentration
- Preparation of a final product or production of different qualities (diamonds, precious stones, industrial minerals)
- "Near-to-face processing" (use of sensor based sorting underground and in satellite mining)
- Re-processing of old waste dumps and coarse processing of other products
- Elimination of noxious minerals from plant feed to improve flotation or leaching or from coarse waste for improved deposition quality (e.g., pyrite-containing rocks)
- Diversion of plant feed to separate processing lines according to grade, mineralogical composition or contaminants

Sensor-based sorting is basically a dry process (some versions need a certain amount of water or steam for feed preparation/surface cleaning). This enables its use in desert, arid or permafrost areas.

Ore sorting-plants can be built very compact, for example in containers for mobile or semi-mobile applications. They can be fit into a tight space in underground installations. Waste can be dumped directly underground and used for backfilling, and shaft capacity for the ROM can be increased.

EMERGING APPLICATIONS AND ONGOING DEVELOPMENT

Increasing throughput is a constant requirement from all operations of massive resources like copper or iron ore. At current throughputs, the required capacity can only be provided by a number of parallel sorters. Increase of throughput can be done by optimizing material presentation, i.e., faster presentation speeds, hardware and software.

In the field of sensors, there are numerous simultaneous developments. For many applications, the line-scan camera is sufficient. When optical properties differ relatively little, laser based sorters can be an option. As a sensor for primary surface properties, NIR sensors are increasingly used. Additionally, "hyper-spectral imaging" technology, which is used in airborne geological measurements, is evaluated for sorting and quality control applications. In both types of multi-spectral detection, the critical point is data filtering and evaluation to reach a sorting decision in near real time.

A good potential for sorting applications is related to XRF sensors. Although it is a particle surface detection method, it comes close to the minerals processor's dream: To sort according to chemical composition and grade. Compared to its use for laboratory analysis and process control, the required measuring time is extremely short despite low spatial resolution of currently several centimeters, which leads to low signal-to-noise ratios. Nevertheless, it is possible to measure heavy elements, not based on the absolute, but relative counting rate. The lowest detection limit is reported to be about 0.1%. A disadvantage is the relatively low throughput of the actual industrial machines, where the particles are presented in a row of channels to the detectors, see Figure 7. At least 200 XRF sorters have been put in operation in the last two decades; an example is shown in Figure 8.

For metal ores and coal, XRT has shown very good results in industrial plants, like in the Mittersill scheelite mine (Austria) (Mosser 2010). It can identify elements according to their atomic density. Especially heavy elements, like tungsten, absorb x-rays nearly completely. Tungsten minerals like scheelite or wolframite can be recognized as black or grey dots within a rock and can be identified by their contrast to the matrix. The separation of light coal and heavy stone works well (and in relatively dry condition). First trials with diamonds have shown good results. The potential for sulfide and metal oxide ores (cassiterite, tantalite, etc.), and also for industrial minerals like barite or fluorite has been successfully evaluated in laboratory tests, but is still not used industrially.

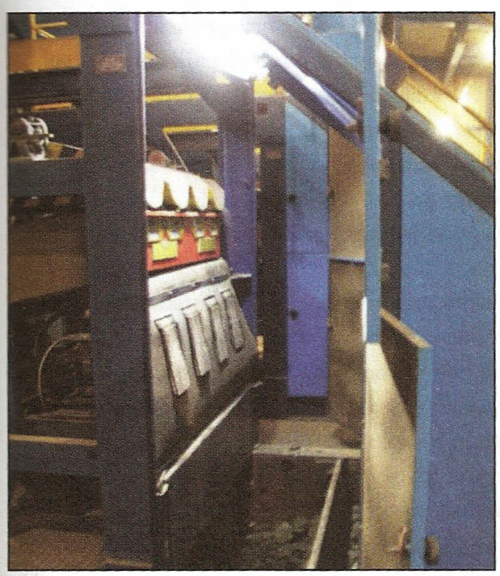

Figure 7. XRF sorter with channel feed and mechanical flaps

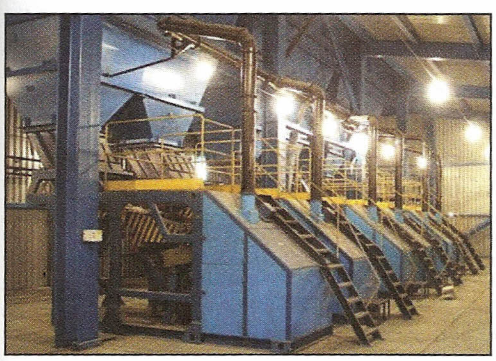

Figure 8. Six XRF sorters working in parallel

Because of the very short measuring times compared to laboratory use, it is difficult to detect low grade values, such as for precious metal ores or other low-grade metal ores. To distinguish between ore and waste or between low and high grade ore it is still possible using "indirect" detection. Indirect detection means that not the target mineral or metal is detected, but some other "indicator mineral," or generally, an "indicator property" tells the sorter if this is a piece of ore or waste. One example is the detection of ore by alteration minerals, which can be detected by NIR sensors without being able to measure e.g., the copper content.

Combinations of sensors are possible. The combination of optical and NIR/optical is already the state of the art, as well as optical/inductive or XRT/inductive sensors. More than two sensors are currently not used in order to limit the effort and time for data processing. Whenever possible and acceptable, the aim is to use only one sensor to keep the set-up as simple and fast as possible.

As mentioned above, LIBS (Laser Induced Breakdown Spectrometry) could be the next sorter development. A future project is pattern recognition. To distinguish, for example, between fine grain, coarse grain or layered rocks is an easy task for the human eye, but a challenging one for image processing.

System Integration

Sensor-based sorting should play a major role in "mine to mill integration" (Bamber 2008, Kleine 2010):

- It may be integrated into the mining and backfill methods
- Adaption of downstream processes
- Consideration in the first planning steps of the processing plant and the mine
- Consideration of ore sorting in pre-feasibility and feasibility studies

SUMMARY

Several factors inhibited the wide-spread use of ore sorting technologies during several decades until the turn of the century. Entrepreneurs originated the first industrial purpose-built sorters, such as the uranium ore sorter. Food sorting machines were also adapted to heavier duty uses as required to stand up to conditions in ore processing plants. A major advance was achieved with the fast scanning laser sorter, although the number of applications was limited. Just over 30 sorter machines were in use for magnesite, limestone, phosphate, tungsten ore, lignite coal, talc, a gold ore in an underground mine, a lead-zinc ore in a similar situation and spodume-containing pegmatite ore until about 1990.

When microprocessors, advanced line-scan cameras and improved light sources became available, machine construction cost was substantially reduced. This made it possible to extend sorting to lower capacity sorting, such as for smaller particles than what prior art machines could do economically. Several small, entrepreneurial type companies entered the ore sorting market. In addition, sensor technologies were further developed, driven by the need to replace labor in government mandated waste recycling programs. With a broad industrial basis for such advances, adaptation to ore sorter applications became a natural consequence, just as in the beginning of the ore sorter history when food sorters formed the industrial technological basis. Therefore, it is anticipated that ore sorting will no longer be a niche unit operation in the mining industry.

ACKNOWLEDGMENTS

Illustrations were from personal files, Internet publications, and some from unnamed but gratefully acknowledged ore sorter vendors.

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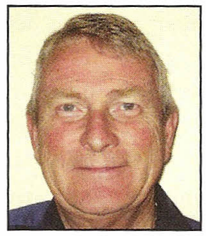
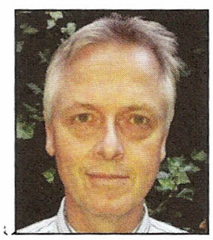
ABOUT THE AUTHORS



Bo R. Arvidson has degrees from the Royal Institute of Technology (KTH), Stockholm, Sweden, and has more than 45 years of experience in the minerals industry. In 1974, he joined Sala International and was assigned to Sala Magnetics Inc. in the USA, and later became the technical director of the group. He has also worked for Amax Extractive R&D in Colorado, USA, and the Bateman Company. At Bateman he developed new high-intensity magnetic separation technologies and associated applications. He later returned to Colorado and built up Bateman's business specializing in the new magnetic separation area, ore sorting, and additional technologies such as linear screens and inter-stage carbon screens. In 1990 he formed his own company, International Process Systems Inc. (INPROSYS), which successfully developed, manufactured, and marketed advanced high-intensity magnetic separators. He was engaged in eddy-current separator technology, high-efficiency air classifier development, and photometric sorting, and developed more than 60 new industrial applications. The company was sold to Outokumpu Technology (now Outotec) in 2001 and he managed the merged Physical Separation group for 4 years. He then began his own consulting business.



Hermann Wotruba has a degree in mining engineering from the RWTH Aachen, Germany, where he also obtained his PhD in mineral processing. After 9 years working in industry, he went back as a full professor and head of the mineral processing group in 1998, which is his current position. He has extensive experience in the area of mineral processing and environment with project experience in many regions like South America, Southern Africa, and Asia. His work includes mineral processing base studies to flow-sheet development, equipment and plant design, plant commissioning and optimization, and environmental management with special emphasis on dry mineral processing and sensor-based sorting. He is one of the world's leading experts in small-scale and artisanal cleaner mining and processing technology and member of the International Mineral Processing Council.