DOBBINS, M., DUNN, P., and SHERRELL, I. Recent advances in magnetic separator designs and applications. *The 7th International Heavy Minerals Conference 'What next',* The Southern African Institute of Mining and Metallurgy, 2009.

Recent advances in magnetic separator designs and applications

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Magnetic separation equipment has long been used to upgrade and beneficiate a wide variety of minerals and materials. Over the years, significant advances in both wet and dry magnetic separators have improved their operability and separation performances, broadening their use. However, certain areas of weakness still remain, including: fine particle processing, high temperature limitations and suboptimum separator designs.

This paper will provide a brief look at existing technology and highlight some key areas where room for improvement exists. Recent novel magnetic separator technology developments aimed at addressing these limitations will then be explored, and substantiating data discussed.

The recent advances in magnetic separator developments highlighted in this paper show that, through continued development, traditional processing obstacles can be hurdled allowing for more efficient and robust minerals processing solutions.

Existing technology

Magnetic separation equipment for minerals processing generally falls into three basic categories: low, medium and high intensity, based on the relative magnetic field strength employed to accomplish separation. Low intensity magnetic separators (LIMS), are generally wet separators and are commonly used for concentration of magnetite, or for scalping of ferromagnetic materials. The LIMS are high capacity units and simple to operate, so they serve these relatively straightforward applications well. Medium intensity magnetic separators are most commonly dry, rare-earth based drum magnetic separators (RED) with common applications in highly paramagnetic mineral applications including ilmenite, chromite and garnet processing. These RED designs, similar to LIMS, are robust and typically offer high capacity and simple operation. High intensity magnetic separators may be wet or dry. High intensity dry magnetic separations are carried out with induced-roll (IRM) or rare-earth roll (RER) magnetic separators, though the latter is far more common (Dobbins, Sherrell 2009). The RER is known for efficient separations with weakly paramagnetic minerals, albeit it at somewhat lower capacity than low and medium intensity magnetic separators. RER units are most commonly employed in cleaning zircon, silica sands and a variety of other industrial minerals. Wet, high intensity magnetic separators (WHIMS) generate high field strengths and pass slurry through matrix arrangements to collect the magnetic fraction. WHIMS are traditionally applied in mineral sands to collect ilmenite in the early stages of a flowsheet, and have a host of other common uses including iron ore (haematite) beneficiation.

Room for improvement

Feed characteristics

Finer particle sizes

A common problem in minerals processing is the efficient recovery of mineral values in the fines fraction, commonly thought of as <74 μm (200 mesh). The presence of fines is either related to the ore deposit characteristics, or caused during the grinding process in hard rock flowsheets. As a general statement, traditional mineral processing techniques become increasingly inefficient as particles sizes are reduced, resulting in unacceptable grades and/or recoveries below certain size thresholds.

Temperature limitations

Dry magnetic separators suffer from temperature limitations, either because the rare-earth magnets suffer irreversible loss of magnetism at elevated temperatures, or because the materials used in electromagnets cannot withstand intense heat. Caution is taken in defining these limitations and to ensure process conditions are controlled to make certain magnetic separators will not be damaged by high feed temperature excursions. Typical temperature limits are 120–150 degrees Celsius, which, in some cases, does not allow for straightforward installations. Temperature management to enable dry magnetic separation can involve added costs if feed cooling is required, particularly in cases where downstream process operations require additional energy input to re-elevate the material temperature.

RER concerns

Belt concerns

The traditional RER can offer high magnetic strength, since there is essentially zero clearance between the magnetic roll and the inner belt surface, unlike the drum type separator that requires some clearance for proper operation. The belts on an RER are purposefully as thin as is tolerable to ensure minimal interference with magnetic forces. Unfortunately, this same benefit of high strength can also become a weakness.

Conventional RER separators often suffer from belt wear issues due to their open design, which can allow airborne magnetic fines to travel and adhere to the magnetic surface, under the belt, which can be detrimental to both belt life and separation efficiency. While there, this material can cause premature belt wearing, and, as it builds in thickness, increase the distance from the magnet to the particles being separated on the outside of the belt. While RER machines are relatively low maintenance, belt wear issues related to fines within the feed can become costly, and in dusty applications, belt replacements can average near 40 per cent of annual RER maintenance costs (Dobbins and Sherrell, 2009).

Static charging

Static charge build-up between the surface of the RER belt and fine particles can also be detrimental to separation efficiency. When feed travels the length of the belt to the magnetic zone, particles rub together creating a static charge (triboelectric charging) that can cause the fine non-magnetic/non-conductive particles to adhere to the belt surface and interfere with separation efficiency (Figure 1). Ionizers can be used to disrupt this charging phenomenon, but in many cases do not completely eliminate the separation efficiency impact. (Dobbins and Sherrel, 2009).

Feed bed make-up

Compaction of the feed bed on the RER belt can lead to non-magnetic particles becoming 'held' within the bed of material, and segregation of the feed bed can lead to finer particles reporting to the bottom of the material bed (Figure 2). Both compaction and segregation reduce separation efficiency by preventing the release of nonmagnetic particles from the belt and thus increasing entrainment of non-magnetic particles into the magnetic stream.

WHIMS concerns

Particle collection capacity

During WHIMS processing, the balance between hydrodynamic drag force and magnetic attraction force tilts in favour of the drag forces, so maintaining adequate capacity requires a higher magnetic field gradient to attract weakly magnetic particles. As the magnetic force increases, its effective range decreases, so more points of collection are required to maintain effective particle collection. With the commonly used grooved matrix plates, even at 12 grooves per inch (a common size for particles near 100 μm), there simply are not enough collection points to effectively overcome the opposing physical forces within the magnetic zone. The only combative solution is to reduce separator throughput to avoid large reductions in separation efficiency.

Matrix plugging

In some cases, to overcome capacity issues, different matrix materials (e.g. steel wool) are used to increase the number of collection sites. Unfortunately, more collection points means smaller gaps within the matrix. Once the matrix volume exits the magnetic field, the traditionally relied upon forces of gravity and water flushing to free magnetic particles are often not enough to overcome matrix plugging by larger particles, or matrix blocking caused by conglomerations lodged as lumps into the empty spaces of the matrix. Additionally, magnetic flux leakage in conventional electromagnet designs can generate a sufficient residual magnetic field to inhibit magnetic particle release, even while it is in the washing position and 'outside' of the magnetic zone. These particles can reside in the matrix volume until the magnetizing current is turned off. A blocked or partially blocked matrix leads to a reduction in throughput and efficiency, and will result in eventual machine shutdown for aggressive matrix cleaning.

Particle misplacement

Matrix material configurations that allow for more collection points also have stronger magnetic forces. When these matrices are magnetized and collecting multiple particles at each high-gradient trapping site, non-magnetic particles can also become trapped. This entrainment occurs when fine non-magnetic particles are held close to the matrix by magnetic particles and prevented from flowing through and reporting to the non-magnetic product. Particle entrainment can lead to a reduction in grade and recovery, potentially causing an increase in recirculating loads or requiring additional stages for cleaning or scavenging (Dobbins and Hearn, 2007).

Recent technology advances

High efficiency rare-earth roll separator

Feed system

The proprietary feed system on an Outotec® high efficiency (HE) rare-earth roll is optimized to handle standard feeds or finer feeds (<74 μm) (Arvidson and Zhu, 2007). An adjustable transition chute is located at the roll feeder and at each subsequent separation stage. This chute can be relocated to present material on the belt (like a traditional RER separator) or at any point on the magnet roll, and at varying heights above the cassette (Figure 3). The adjustability of the feed point allows separation performance to be optimized.

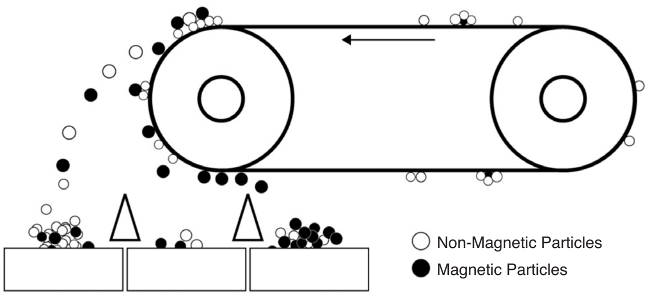

Figure 1. Reduced separation efficiency from static charging of particles (Dobbins and Sherrell, 2009)

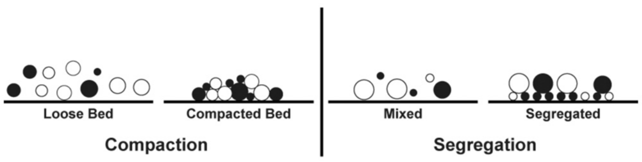

Figure 2. Particle reaction to belt motion (Dobbins and Sherrell, 2009)

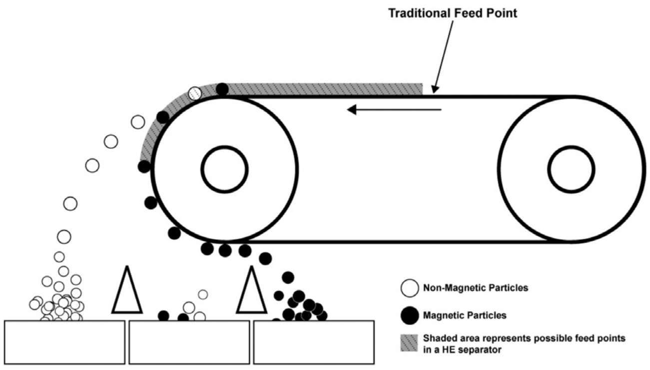

Figure 3. HE RER principle of operation illustrating new range of feed point options

By feeding directly on to the magnetic roll, rather than further back on the belt, belt residence time is reduced. This reduction in residence time minimizes any tribocharging, or static build-up, of non-magnetic materials, thus preventing them from sticking to the belt. Additionally, a lower residence time means the feed bed stays fluid and homogenous entering the separation zone allowing non-magnetic material to more easily leave the magnetic roll. Optimum position of the feed point can be determined during laboratory testing.

Dust control

Several remedies to the dust dilemma have been employed in RER processing over the past few years, such as de-dusting of the minerals prior to separation and adding purge air to the volume between the magnetic roll and the idler roll. the new HE RER has taken these remedies a step further: The entire frame, hopper and door systems are specifically designed to contain fine particles inside the machine. Internally, the units are equipped with a tunable, per-stage dust extraction design, as well as purge air in the cassettes to minimize dust issues. The combined result of these improvements is a much cleaner and safer operational environment, improved part life and sustained separator performance.

Process data

Two heavy mineral samples were tested with the conditions shown in Table I. The ilmenite sample showed similar separation results between the two feed points at lower yields (Figure 4). At higher yields, the separation improved when the sample was fed directly on the magnet roll with less zircon reporting to the magnetic product. The zircon sample also showed improvement when feeding directly on the magnet roll compared to traditional belt feeding with a reduction in both the % Fe_2O_3 (from 0.074% to 0.048%) and % Al_2O_3 (from 0.59% to 0.48%) at similar yields (86%). The % TiO_2 in the zircon non-mag product was unchanged at 0.084%.

FluxForce™hybrid rare-earth magnetic separator

Though the new HE RER design is a great improvement over conventional RER units, some problems still exist. Static charging issues have been greatly reduced and dust issues are much more controlled, but these remedies do not completely address the machine design drawbacks, especially when finer particles, which are becoming more commonplace, are present. The use of belted roll technology, and the openness required of these designs, is simply not ideal for all applications, but, until recently, no alternative existed.

Outotec (USA) Inc. has completed the first prototype of a new design that provides a solution to some of these more difficult applications. The developmental FluxForce™ hybrid rare-earth magnetic separator is a cross between rare-earth roll and drum magnetic separator (Figure 5). The FluxForce™ utilizes an ultra thin and flexible shell that comes in direct contact with a smaller diameter magnetic roll, enabling the belt and idling roll assembly to be eliminated. This magnetic roll is similar to those used in the traditional and HE RER units, offering the same magnetic strength. The ends of the unit are sealed like an RED design, so no dust can collect on the roll. In effect, the FluxForce™ takes the best of both designs and merges them into one machine. This allows RER level field strengths to be applied to applications where previous technology was unacceptable due to contamination from bearing wear and belt material.

Enhanced FluxForce™ feeding arrangement

The 'stepped' nature of RER machines, brought about by the horizontal length of each belted separation module, has somewhat limited plant layout configurations. This geometry also accounts for nearly all RER machines being non-magnetic retreating in configuration, with little

Table I
Test conditions

Mineral	d_{50} (μm)	Feed rate (tph/m)	Roll speed (rpm)	No. of passes
Zircon	98	5	119	1
Ilmenite	114	5	375	1

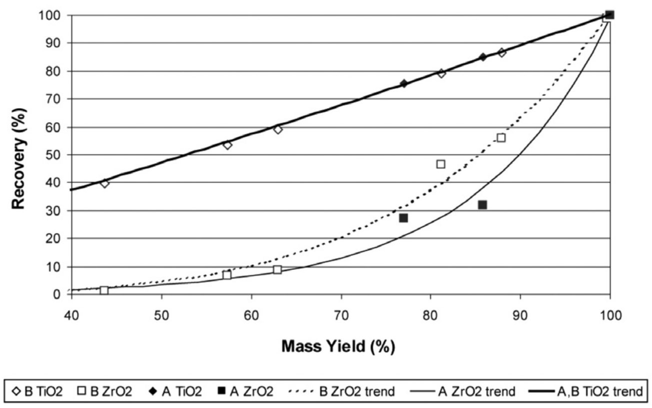

Figure 4. Ilmenite test results. (Dobbins and Sherrell, 2009)

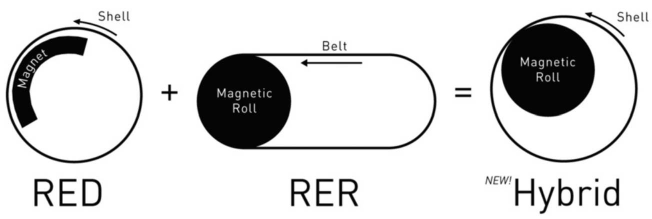

Figure 5. The Outotec® FluxForce™ is a hybrid of the RED and RER magnetic separators

straightforward possibility for magnetic retreat or hybrid variations to be supplied tailored to specific applications. 'Back to back' pairing of machines is used commonly to ensure access to three sides of all units for ease in operation and maintenance.

The compact nature, both horizontally and vertically, of each magnet assembly module used in the FluxForce™ separator will allow the machines to be arranged vertically, and thus with smaller footprints in plant installations. From the viewpoint of feeding arrangement, this will permit realistic consideration of configurations such as 'non-mag retreat,' 'mag retreat,' 'rougher-cleaner,' or 'rougher-scavenger' in the same machine cabinet with alternative chuting, splitters and gating mechanisms. Additional separation stages, beyond the two or three stage RER machines commonly supplied, will be viable without significant increase in headroom requirements (Figure 6).

Process data

To illustrate the potential of alternative configurations, a basic test in ilmenite cleaning was conducted using the FluxForce™ in a traditional three-pass RER non-magnetic retreat configuration versus a hybrid configuration. The hybrid case was also three stages; however, the magnetic products from the first two stages were combined and retreated as the third and final pass. The feed material was a near-finished ilmenite grading 64% TiO_2. The FluxForce™ hybrid configuration case resulted in an additional 1.7% mass yield (1.2% increase in TiO_2 recovery) with the same ZrO_2 and SiO_2 content in the product (0.04% and 0.3% respectively).

Zircon testing was also performed. This compared a traditional two-pass non-mag retreat configuration with a hybrid mag retreat configuration. The hybrid mag-retreat configuration resulted in an increased mass yield of 4.9% while producing a better TiO_2 and Fe_2O_3 product (0.063% and 0.274% respectively vs. 0.070% and 0.300%).

This initial acceptable performance, even in these first stages of development and testing, show promise that the FluxForce™ may be a better option for some applications over the traditional or HE belted RER.

SLon® WHIMS

The SLon® vertically pulsating high gradient magnetic separator (VPHGMS) system is a unique WHIMS design employing a vertical carousel, straightforward rod matrix system and pulsation mechanism. These variations to traditional WHIMS designs help the SLon® systems achieve high capacities and improved separation performance in a straightforward, simple to operate system. In addition, the specific features of the SLon® that differentiate it from traditional, horizontal carousel WHIMS machines make it more suitable for effective treatment of very fine feed streams.

Vertical carousel

The carousel is arranged in a vertical orientation as opposed to a traditional Jones-type WHIMS, which uses a horizontal carousel. The vertical nature of the carousel allows for magnetics flushing in the opposite direction of the feed (near the top of rotation), enabling strongly magnetic and or coarse particles to be removed without having to pass through the full depth of the matrix volume. In addition, the magnetics flushing is accomplished in a location with low stray magnetic field to reduce any residual grip on the magnetic particles (Figure 7).

Matrix

The SLon® utilizes a filamentary matrix constructed of rods ranging in diameter from 1–3 mm to accommodate various size ranges of feeds. The rods are orientated perpendicular to the applied magnetic field in a fixed, equidistant pattern to enable optimum magnetic force to be achieved while minimizing the risk for entrapment of particles, especially when compared to randomly positioned filaments (wool) or expanded metal sheets (Figure 8).

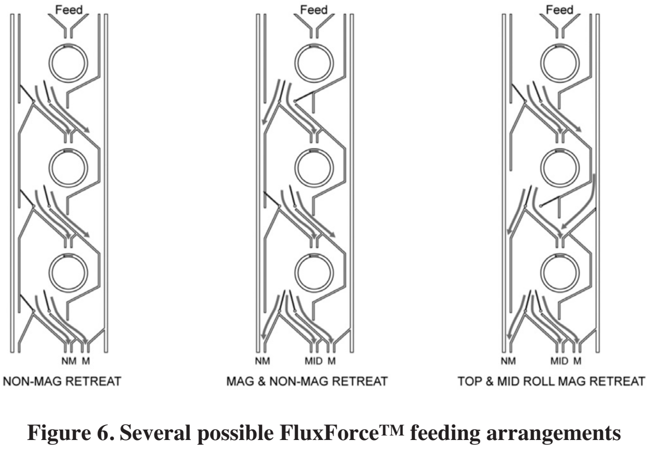

Figure 6. Several possible FluxForce™ feeding arrangements

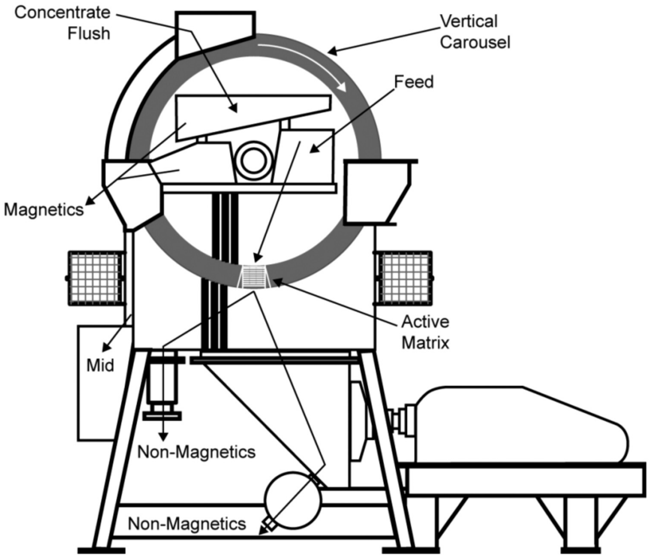

Figure 7. Vertical carousel of the SLon® VPHGMS

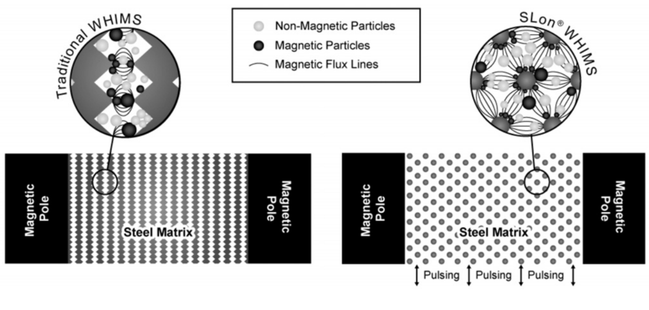

Figure 8. WHIMS matrix comparison. (Elder, 2006)

Pulsation

An actuated diaphragm provides pulsation in the separation zone to assist the separation performance by agitating the slurry and keeping particles in a loose state, minimizing entrapment. This mechanism also maximizes the particle accumulation (trapping) on all sides of the rod matrix creating more usable surface area for magnetics collection (Figure 9).

SLon® performance data

Process data: zircon example

On a scavenged stream, rich in zircon, tests were conducted using SLon® VPHGMS equipment to enrich the zircon content at high recovery, while rejecting troublesome TiO_2 containing minerals problematic in re-feeding the dry separation plant. The feed was approximately 59% zircon mineral, with 8% each of ilmenite and leucoxene. Figure 10 shows the test results with varying field intensity (0.3–0.9 Tesla) on mass yield and zircon recovery, as well as ilmenite and leucoxene rejection.

A pronounced benefit at the 0.7–0.9 Tesla range was seen with zircon mineral grades of 70–75% produced. A few percentage points of zircon recovery were lost (dropping from 95 to 92%), while the mass yield dropped 6% from 80 to 74%. Ilmenite rejection, as expected, was high at 93%; however, the most significant impact was the leucoxene rejection jumping sharply from 8 to 23%. This latter finding is significant for operations where the highly altered titanium minerals are causing problems in producing premium zircon products at reasonable recoveries in the dry separation process.

Process data: ilmenite example

SLon® VPHGMS testing was conducted on a heavy mineral concentrate sample for ilmenite removal prior to downstream processing operations. The feed material was approximately 63% ilmenite, 2% leucoxene and 5% zircon. Several tests were conducted, varying the number of passes (non-magnetic retreat configuration), the magnetic field intensity per pass and the pulsation setting. As expected, ilmenite recovery was highest (up to 99%) with multiple passes at higher field strengths. Zircon rejection was optimized through multiple passes with aggressive pulsation settings, as the pulsation action gave the non-magnetic particles a higher probability of not becoming entrained.

In several cases, it was seen that the highest field strengths did not always produce the optimum compromise between ilmenite recovery and zircon rejection. Depending on the ranked priority of separation objectives, and the willingness to consider multiple stages of separation, the data shows that there are several influencing parameters that should be tested and optimized to ensure the best possible solution for reaching desired recovery and grade (Table II).

PyroMag™

As stated previously, commonly available dry magnetic separators suffer from temperature limitations. There are, however, instances where high-temperature separation is desired for overall reduction in plant energy requirements and thermal energy savings would result from elimination of the cooling-reheating process surrounding magnetic separation.

One such example is the separation of magnetic material from char in various metallurgical processes at high temperatures, where the current convention involves a cooling step prior to magnetic separation. The desired materials in these cases have high magnetic susceptibilities, such as iron and partially metallized ilmenite, which are separated from char, silica and other non-magnetic

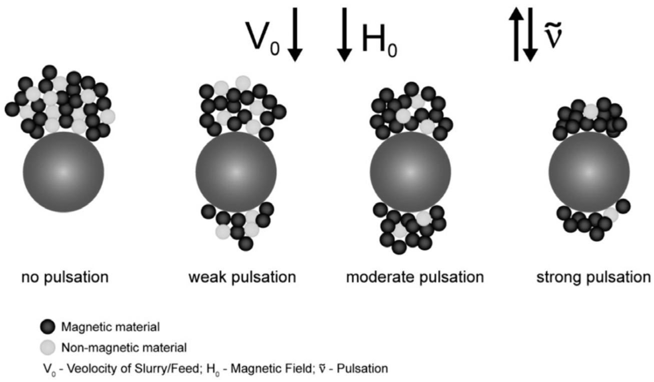

Figure 9. Particle loading on pulsing matrix. (Dahe, *et al*., 1998)

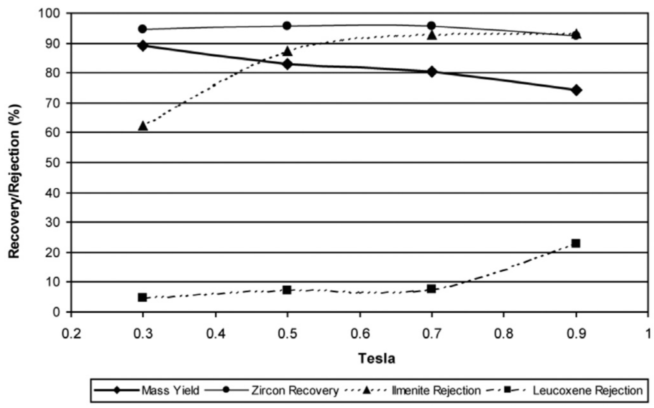

Figure 10. Zircon test results using SLon®

Table II
Ilmenite test results

No. passes	Tesla (1st, 2nd, 3rd pass)	Pulsation (1st, 2nd, 3rd pass)	Mass yield (all mags)	Ilmenite recovery	Leucoxene recovery	Zircon rejection
1	0.8	230	83.42	88.71	64.46	44.19
2	0.8, 0.8	200, 200	95.33	99.70	52.37	32.58
2	0.4, 0.6	230, 230	87.34	96.16	45.90	43.17
3	0.2, 0.4, 0.5	250, 200, 200	90.81	97.27	49.85	35.64
3	0.2, 0.4, 0.5	250, 230, 230	86.5	94.8	58.9	59.7

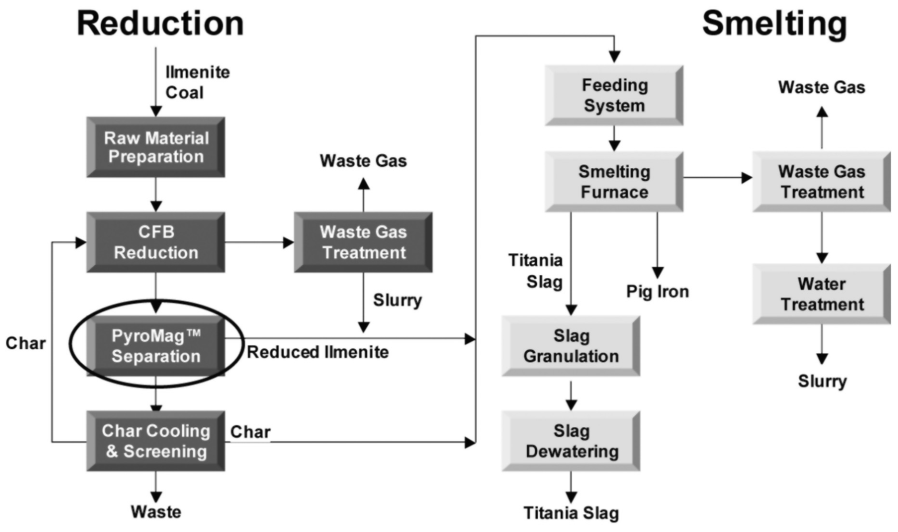

Figure 11. PyroMag™ shown in the Circosmelt® process

contaminants. Outotec's Circosmelt® (ilmenite) and Circofer® (iron ore) are examples of two metallurgical processes that would benefit from a magnetic separator designed to operate at extreme temperatures (Figure 11). An estimate of the energy savings that could be realized by feeding hot reduced ilmenite directly to a magnetic separator is ~330 kWh/t of TiO_2 slag which equates to US$3.2M per annum (US$0.04/kWh) for a 250 000 t/a slag furnace.

Outotec's PyroMag™ separator has been purpose-designed to fill this void (Dierickx and Grey, GREY 2009). Special materials of construction are used for surfaces in direct contact with the feed material. A thermal shield and liquid cooling circuit (with chiller) are used to keep the magnet assembly cool while purging is employed to remove heated air. Double wall construction of the machine allows for safe access and operation of the unit, and high temperature bearings are used to ensure robust operation.

A prototype PyroMag™ has been installed in Outotec's pilot-plant facility in Germany and run at elevated temperatures up to 450 degrees Celsius to verify the designed capabilities (Figure 12). Although temperatures tested were somewhat low, the design basis should allow for efficient separations exceeding 700 degrees Celsius.

Though the separation itself is straightforward, basic tests were conducted to ensure that the PyroMag™ separation was as efficient as in 'cold' RED tests. Figure 13 shows that the separation of reduced ilmenite at elevated temperature was 99.5% efficient, as the residual non-mag only produced 0.5% weight as misplaced magnetic fraction.

Summary

Magnetic separation equipment plays various important roles in mineral processing flowsheets. Many recent advances in both wet and dry magnetic separators have continued to broaden their use. The HE RER improves overall separation by increasing the ability to treat finer particles by adjusting the feed position from the belt to the magnetic roll. The FluxForce™ development addresses ongoing issues with belted RER separators by using an enclosed shell in direct contact with a rare-earth roll magnet. This allows high magnetic force for separation purposes while removing costly belts (and idler rolls) and enclosing the cassettes to reduce the effect of dust. The SLon® VPHGMS allows improved separation, particularly in finer particles size ranges, over traditional WHIMS through a vertical carousel, rod matrix and pulsation mechanism. The PyroMag™ allows magnetic separation at extremely high temperatures as a way to reduce cooling and reheating costs in specific applications. This continued development of magnetic separation technologies is leading to new designs that both improve separation and reduce costs.

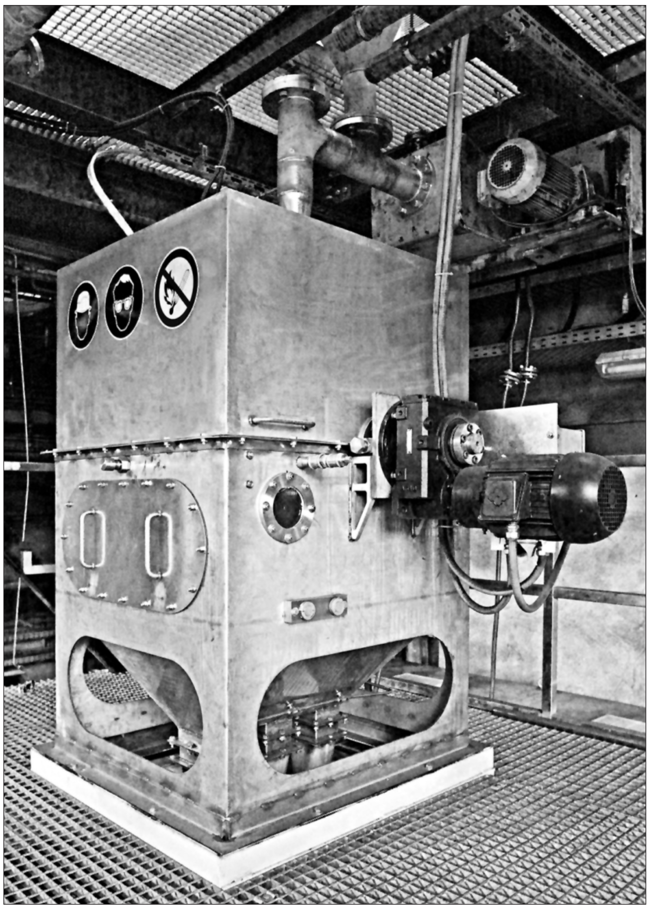

Figure 12. PyroMag™ pilot separator at Outotec research centre in Germany

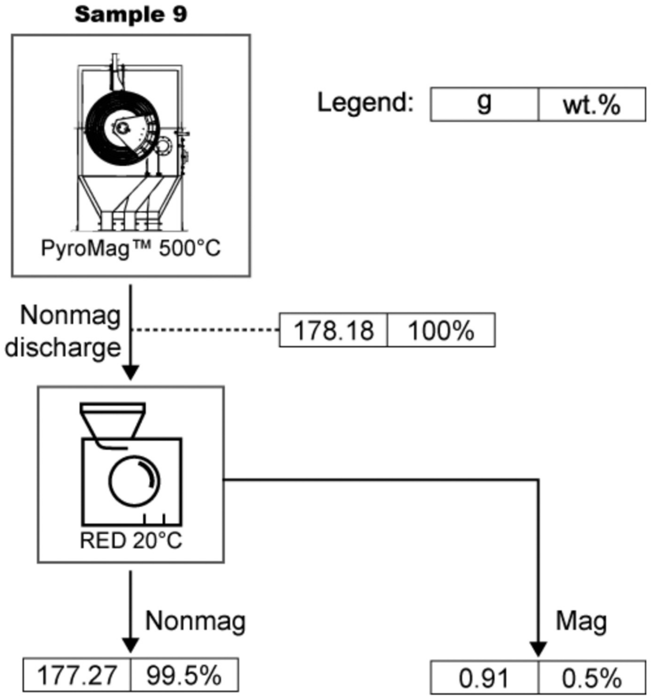

Figure 13. PyroMag™ test results

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Peter attended Virginia Tech and graduated with BS & MS degrees in Mining and Minerals Engineering in 1994 and 1996. He immediately began employment with Dupont in the Titanium Technologies business at the Starke Florida mineral sands operation, later transferring within the company downstream to the Delisle Mississippi pigment plant operations. He spent 10 years with Dupont, starting with R&D and project assignments and concluding with management responsibilities in the 'coke&ore' and chlorination reaction units. Following a successful spring 2006 restart of the Delisle operations following the Hurricane Katrina disaster, he joined Outotec in and has now been with Outotec (USA), Physical Separation, for 3 years in Business Development roles.