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Rare-earth magnetic separators for mineral sands applications

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Magnetic separators using rare-earth magnets were pioneered in South Africa in 1981 and have found wide-spread use in the mineral processing industry around the world. The first separators filled a need to treat relatively coarse particles (+2 mm), which was beyond the efficiency range for standard electromagnetic roll separators. Although electromagnetic drum separators were available, their high cost and comparatively low capacity made many coarse particle applications uneconomic. It was soon realized that the new separation technology enhanced the efficiency of many fine-particle applications as well, accelerating the industry acceptance of the rare-earth magnetic separators.

More than a thousand machines are in operation in over one hundred applications presently (1997). It is only during the last few years that the heavy mineral sands industry has embraced the rare-earth magnetic separation technology, although the first installations date back to 1986. The reasons for this slow acceptance, and the sudden accelerated use, of both rare-earth roll and drum separators are discussed.

Available data for primary and secondary ilmenite production, zircon processing, garnet- and leucoxene-rutile separation are presented. Due to restricted information, only a fraction of a wealth of mineral sands data are available for publication. Examples from other applications illustrate the new levels of performance that can be expected from the most recent technology improvements.

A brief review of relative separator performance and operation characteristics is given. Potential future developments are discussed.

Introduction

In the 1970s, rare-earths began to be used in a new generation of magnetic materials, which have unique characteristics. Not only were these stronger in the sense of attractive force between a metallic magnet and mild steel (high induction, B), but the coercivity (H_c) was also extremely high. This property makes the magnetization of the magnet body very stable, (i.e., it cannot easily be demagnetized). Consequently, a piece of mild steel can be magnetized by a rare-earth magnet to a very high degree. It was a known fact that steel can be magnetized by magnets positioned on both sides of a flat steel body. In addition, the steel magnetization could be brought to a high level if the magnet poles were the same on each side of the steel. However, in the past, large magnet volumes were required to achieve any substantial magnetization. With the new magnets, the magnet volume could be much smaller to generate high steel magnetization. In 1981, one of the authors found that the magnet to steel thickness ratio should be 4:1. This ratio would provide maximum steel magnetization (near saturation) when the magnet and steel rings were stacked up to form a roll, (see Figure 1).

One of the first prototype magnetic rolls was calculated to have about 14 000 gauss steel magnetization. It was found in comparative testing with electromagnetic induced roll separators operating at 21 000 gauss that similar performance was obtained in fine particle processing (smaller than 1 mm). When processing coarser particles an improved performance was established, that is, a lower level of weakly magnetic contaminants remained in the upgraded

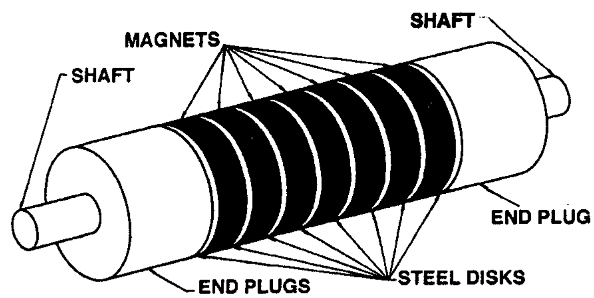

Figure 1. Magnetic roll principle

product. Additionally, a reduced number of separation passes achieved a high quality product. The reason for better performance was that with a rare-earth magnet (REM) roll, there is no magnetic air gap through which particles must pass. With induced magnetic rolls (IMR), the particles are passing through a magnetic air gap, which must be sized to let the particles through. Increasing the air gap rapidly reduces the magnetic flux density. Therefore the magnetic force is drastically reduced when using IMR for large particle processing.

According to magnetic circuit calculations, the steel is more or less saturated (about 20 000 gauss) in most of the present roll designs using Nd-Fe-B high-energy magnets. The drum separator magnet sections may not always include saturated steel segments.

Current rare-earth magnetic separator versions

Besides simple magnetic traps such as grates and grids, which are not included in our discussion, there are three distinct types of magnetic separators using rare earth magnets (all three are seen in Figures 2 through 5):

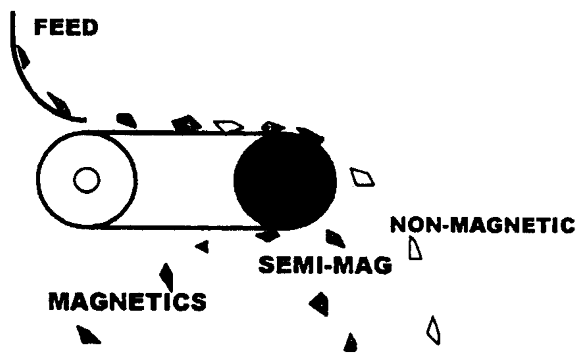

Figure 2. Conceptual diagram showing a typical rare-earth magnetic roll separator

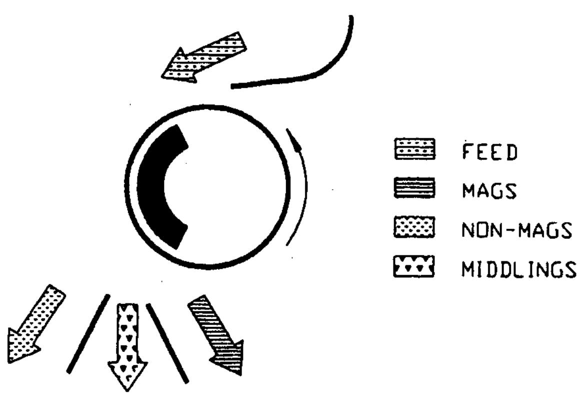

Figure 3. Dry drum separator principle

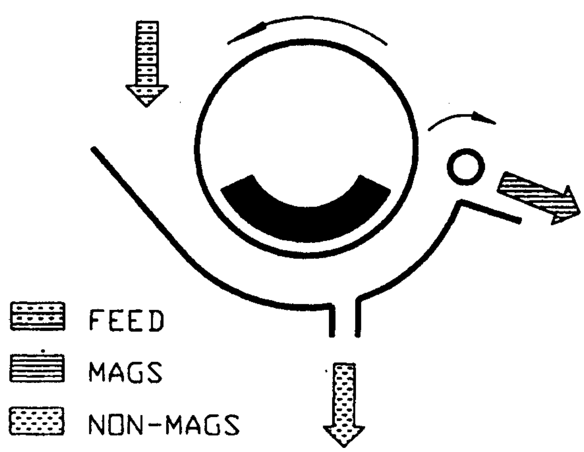

Figure 4. Wet drum separator principle

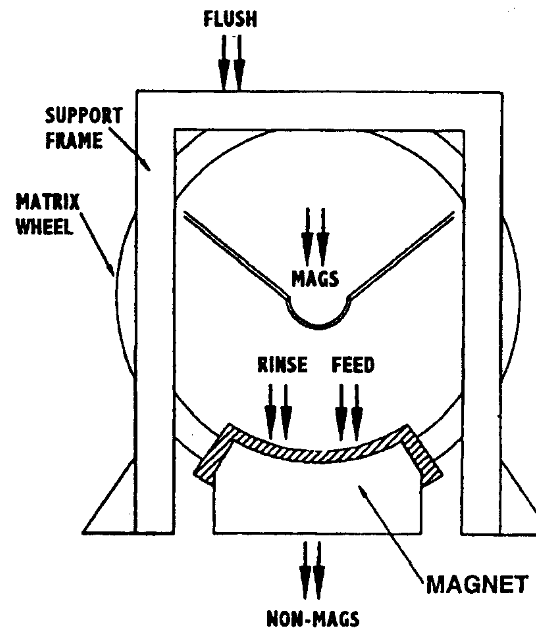

Figure 5. Matrix-type separator

1. Roll separators, usually with an enveloping belt, supported by an idler roll[1-3].
2. Drum separators for dry and wet processing, essentially similar to well-known low-intensity drum separators using ferrite magnets[4,5].
3. Matrix-type separators, such as the narrow-width vertical wheel[2,6].

Of the roll separators, there are at least fourteen manufacturers. Most of the different makes are based on the design concept originated by one of the authors of this paper[1]. Various enhancements have been focused mainly on the belt tracking methods. New magnetic roll configurations and optimization of roll designs are recent innovations that were introduced by INPROSYS. Additional optimization efforts are in progress.

At last count, seven manufacturers have commercially available REM drum separators, most of them based on magnet circuits derived from the use of conventional ferrite magnets. Two unique designs have been presented[4,7] with one offering clear-cut advantages over older designs. Other new designs are rumored, but details are not known.

The matrix-type separator was developed in the 1970s with ferrite magnets. These were substituted by rare-earth magnets in 1984. A few installations are known, but none have been reported for use with heavy mineral sands. The magnetic force is limited to a low level, but may be sufficient for some ilmenite applications. However, we will not discuss this type of separator in detail in this paper.

REM roll separator design and performance characteristics

Although the rare-earth magnetic separators (REMS) of the roll type have been available during the last 16 years the design variations and their associated differences in performance may be divided into four classes:

1. Optimum performance (one maker).
2. High-performance (original maker).

3. Average performance (majority of makers).
4. Poor performance (a few new makers).

The most demanding applications are generally of two types:

A. The magnetic susceptibilities of minerals to be separated are very similar, or even overlap to some extent. Examples: Ilmenite from garnet and ilmenite from hematite separations.
B. The mineral to be separated has extremely low paramagnetic, or diamagnetic susceptibility. Examples: Quartz grains with small inclusions of pyrite or muscovite to be removed in ultra-high purity quartz application.

The uniformity of the magnetic strength is critical for achieving the most efficient separation in both cases. In case B, it is also important to maximize the magnetic force. Differences in performance of various roll separators can often be easily identified when 'difficult' separations are attempted. In direct parallel comparison in pilot plant operations, the class 1 separator, consistently provided distinctly better performances compared to all other classes of separators.

Sometimes, the level of the magnetic strength or the uniformity may not be important (i.e., when the minerals have distinctly and widely different magnetic susceptibilities). In such cases there are very small differences in performance, which may not even be noticeable, between the various class machines. Typically, separators in classes 1, 2 and 3 may yield similar results in 'easy' applications. Such applications may be exemplified by the removal of biotite mica from feldspar and ilmenite-quartz separation. Class 4 separators typically use thick belts, which substantially reduces the magnetic force. Their typically low cost may be attractive in some situations.

However, in 'easy' applications, optimization of *capacity* may result in *lower cost per unit of product*. In one such case in a full-scale pilot plant, a separator in class 1 had more than 250% higher capacity compared to a class 2 (as well as other separators). In full-scale production, four times the capacity was consistently achieved.

Table 1 shows some comparative performance data from feldspar plant operations. Depending on the raw material, the differences may vary. Removal of weakly magnetic constituents, such as muscovite mica, may cause a small change in iron level content, but may be very important for the end user (for example in glaze making).

The specific heavy mineral sands application characteristics are discussed later.

Table I
Comparative performance on feldspar

Case number description	Other REMS TPH/m	High-force® TPH/m	Cost ratio: High-Force®/ other
1. Finnish	3.0	4.0	0.65
2. Italian	3.0	7.5*	0.43
3. Swedish	1.5	3.0	0.61

* In full production, the feed rate averages 12 TPH/m.

REM drum separator design and performance characteristics

The conventional magnet circuit design for drum separators uses radially stacked flat block magnets in axial rows (see Figure 6). Bucking magnets may be positioned between the stacks to force the magnetic field to extend further away from the stacks. By simply substituting some or all of the ferrite magnets with rare-earth magnets, the magnetic field strength could be increased to various degrees.

The drum shell must be thin and the clearance between the shell and the magnetic section must be small, because the magnetic flux decreases with distance from the magnetic section. As the magnetic force field has a short range, thick shells would reduce the effective magnetic force. However, with very thin shells, the wear life will be short. In one case, the shell was completely worn after two months of operation. This was due to improper magnetic section design, which did not enable release of highly magnetic particles. Adding a wear liner is often desirable and whenever possible the magnetic strength design should therefore allow for the thickness of a possible liner.

The first rare-earth magnetic drum separators (REMDS) were used for relatively easy, dry garnet and ilmenite separations, requiring modest magnetic strength. Since then, attempts were made to use them for other applications with limited success. Wet drum separators have found use as higher-powered scalper separators for removal of ferromagnetic material in the feed to wet high-intensity magnetic separators (WHIMS) of the matrix-type. Such separators tend to plug up due to inefficient release of ferromagnetic material. This material is captured in the matrix even at low magnetization in the 'zero-field' zones[6]. One low-strength wet drum separator is being used in a mineral sands application, removing chromium-bearing particles. Many other applications are being explored.

The largest drum diameters known at the time of writing are 1 050 mm (41") and 980 mm (38.5"). The larger diameter has a low-strength magnet circuit. Prototypes of higher-strength separators of the 980 mm diameter size are being field tested. The large diameter size will enhance the capacity of REMDS several times over the more common size units (i.e., in the range of 250 (10") to 610 mm (24") diameter).

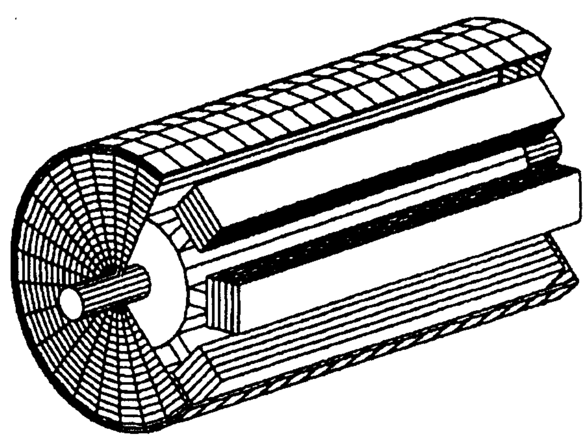

Figure 6. Magnet circuit design for drum separator

Heavy minerals sands processing with REMS

The first known attempts to apply a REM roll separator to a heavy mineral sands application were made in South Africa and Western Australia in 1985. At that time, an ilmenite beneficiation process, which was normally achieved with cross-belt separators, was tested with a full-size machine. The performance was not good because only a single separation pass was used. Since a large amount of magnetic material needed to be removed (more than 85% of the feed), and only a low roll speed was applied, the result was an excessive loading of magnetic particles on the magnetic collection sites (see illustrations in Figures 7a and 7b). As the first generation REM rolls had only 20% of the total roll surface available for attracting magnetic particles, it is easy to realize that a large amount of nonmagnetic particles could be trapped among the highly magnetic ilmenite particles as illustrated in Figure 7a.

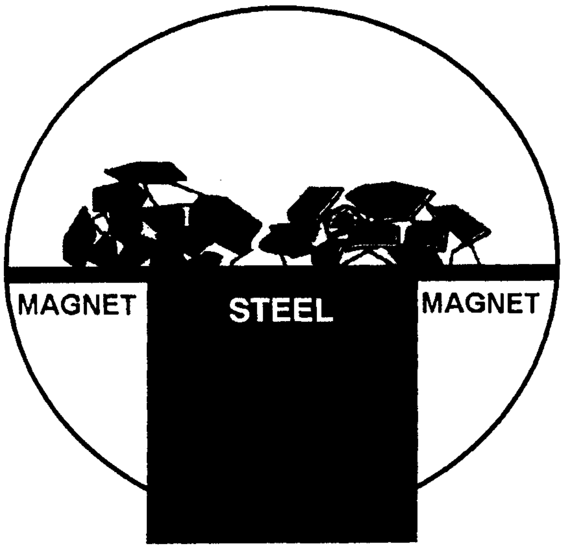

Figure 7a. Overloaded collection sites

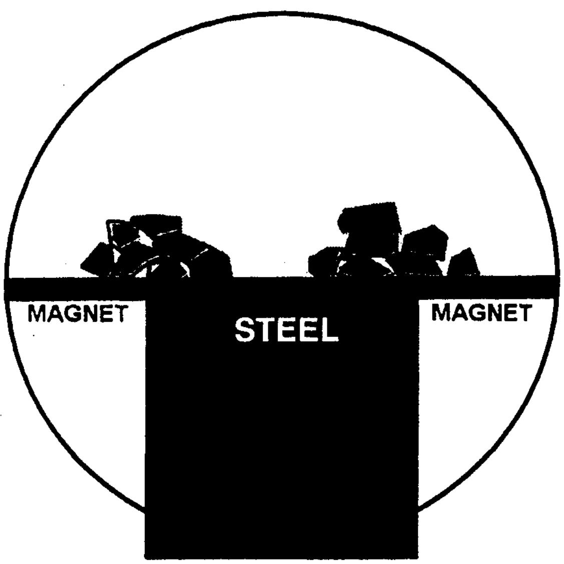

Figure 7b. Optimum loading of collection sites

By the time one of the authors became involved in the Australian trials it was too late to take any corrective actions regarding test procedures. A year later, new testing under proper guidance was initiated with outstanding results. What was different? First of all, it is well known that if too great a magnetic force in relation to the counteracting inertia forces ('centrifugal forces') is applied, the magnetic particles are attracted too strongly and will lock in some nonmagnetic particles as illustrated in Figure 7a. This was easily remedied by using much higher roll speeds and a thicker belt, see Figure 7b, which of course had a more attractive life time than thin belts. High roll speeds translate into much higher feed rate capability as well.

It is also a well-known fact that it is usually far better to use multiple pass separation than a single pass, when a large amount of material has to be removed from the feed stream. Figure 8 shows that a multiple-pass separation provides a more selective separation than a single pass, even if the feed rate is increased in proportion to the number of separation stages used.

By optimizing the roll configuration to a higher level, the performance was further enhanced last year (as shown in Figure 9). When the company, Westralian Sands Ltd, decided to proceed with a full-scale operation (replacing the cross-belt separator plant), the optimized roll type developed by

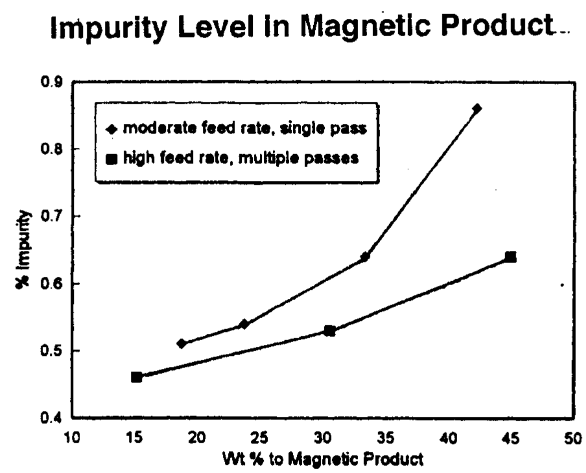

Figure 8. Effects of single versus multiple passes on high-grade magnetic product quality

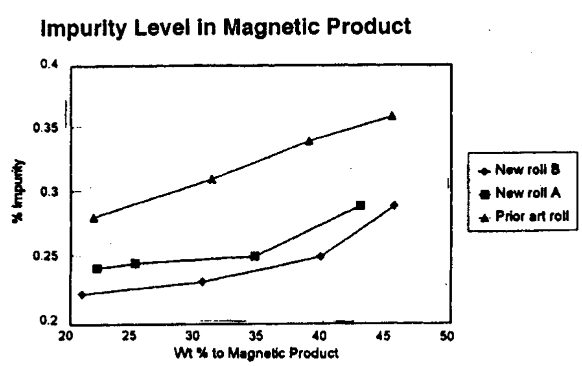

Figure 9. Improved roll configurations enhances separation efficiency

our company was selected. A similar optimization effort has already led to two major mineral sands processing installations in South Africa. We have found that processing ilmenite, rutile, zircon and monazite materials from different sources may warrant an optimization study in each individual case. The 'one-size-fits-all' mentality still exists, but is giving way to the engineered approach that we promote.

Only one major heavy mineral sands case is known where both REM drum and roll separators were installed, but no optimization effort was undertaken. The client would not accept separators using belts (except in situations where the drum separator would have inadequate strength) despite the 10 years excellent track record at Westralian Sands Ltd. The use of proper belts, our REM roll separators and reasonable process control would have been a superior alternative to drum separators. In fact, the process control requirement is less strict for REM roll separators than for the drum separators selected.

Small-scale use of both REMS roll and drum separators have been common in the heavy mineral sands industry, mainly in South Africa, but also in Australia. Usually, these separators were applied to solve bottlenecks in the process, or to modify the product quality after processing with conventional equipment, such as cross-belts or induced magnetic roll separators. The small size and high capacity capabilities were attractive for such retrofits. One of the first installations of this nature was at RZ Mines in Australia. A performance comparison between conventional IMR separators and the earliest type of REM separators is shown in Table II. Additionally, the REM separator was tested on zircon sand with the results shown in Table III.

Table II
Comparison of IMR and REMS results on ilmenite/rutile separation

Separator/ Product	Feed rate TPH/m	Weight %	Amount of non-magnetics %	Amount of magnetics %
IMR	2.7	100		
Magnetic		25	2.5	
Middling		10		
Non-magnetic		65		0.5–0.6
REMS	4	100	0.46	
Magnetic		30.5		
Middling		0.8		
Non-magnetic		68.7		0.28

Table III
Zircon REM roll separator test data @ 2 Tph/m

Product	Weight distribution %	Zircon grade %	Magnetic content %
Feed	100	93.24	(6.76)
Magnetic	5.9	No zircon detected	100
Middling	0.8	Magnetic zircon	(±100)
Non-magnetic	93.3	99.94*	0.06**

* Clean zircon **Magnetic zircon

As mentioned, the graph in Figure 9 shows recent improvements in processing heavy minerals by applying more advanced magnetic roll configurations than typically provided by class 2 and 3 roll separator makers. In fact, in some heavy mineral sands processes, far superior performance has been achieved than with any other type of high-intensity magnetic separator (other REM roll and drum separators, induced roll and cross belt separators). Unfortunately no data has been released for publication.

One new entry in the heavy mineral sands industry provided preliminary data to illustrate the information that may be obtained from a few preliminary, low cost and quick tests. Optimization of roll and flow sheet configurations would be the next step, which would yield an even more interesting performance. Considering first the various size fractions of ilmenite gravity concentrate, two applications were studied: ilmenite beneficiation by processing a heavy minerals gravity primary concentrate and processing conductors from a rutile circuit. The first graph (Figure 10), shows the TiO_2 grade–distribution relationship. Evidently, the first magnetic product (the highest susceptibility material) has low Ti content and the next graph explains why (Figure 11). This product has a high Fe content. Even the subsequent products (lesser susceptibility) have a high iron content. This is an indication that perhaps an additional process step may be required, e.g., roasting, to obtain a high-grade TiO_2 product. Since additional processing is costly, it is desirable to reduce the amount of material requiring such other processing. A magnetic preconcentration step would reject

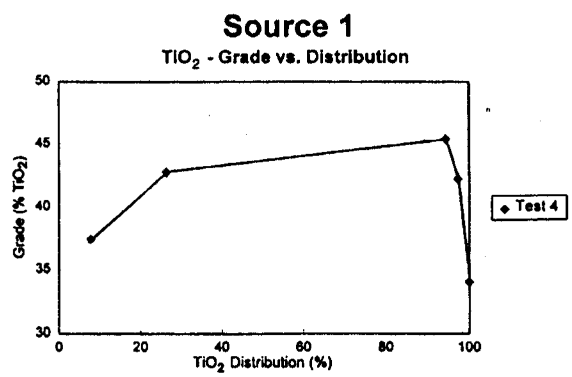

Figure 10. Cumulative Ti grade and distribution in sequential magnetic products

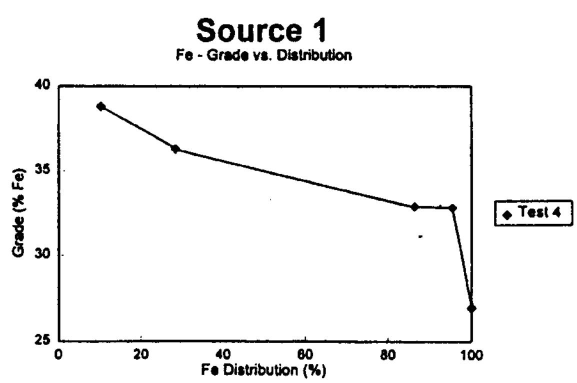

Figure 11. Cumulative Fe grade and distribution in sequential magnetic products

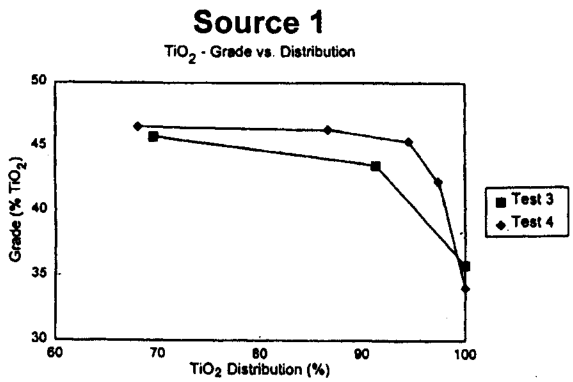

Figure 12. Cumulative Ti grade and distribution by combining magnetic products with descending grade

a large portion of undesirable material. By relating the grade–distribution data with the highest grade of Ti and combining the various streams (Figure 12), it is possible to obtain information to direct the flow sheet development. The purpose would be to maximize the recovery of an acceptable ilmenite grade product.

Similarly, the Ti contents of magnetic products obtained by processing conducting fractions in the rutile circuit show that a product with a somewhat higher grade than 97.5% is possible at high recovery (see Figure 13). The misplaced zircon may have ilmenite inclusions in large amounts, as the zircon tends to report into highly magnetic products (see the graph in Figure 14).

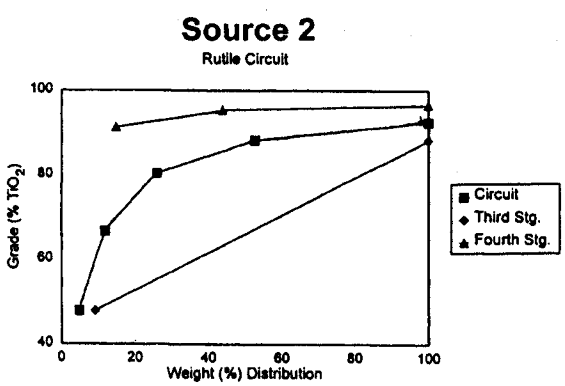

Figure 13. High-grade Ti products from 4-stage processing

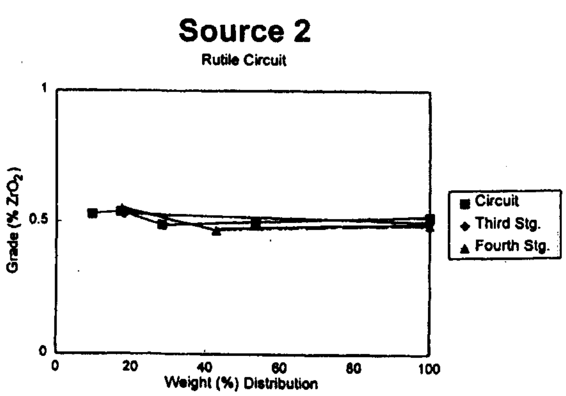

Figure 14. Zircon distributed evenly in all products

A South African mineral sands operation conducted carefully controlled test work with materials in their zircon circuit. One test series demonstrated the importance of using conditions that preclude too much entrainment of nonmagnetic particles when removing magnetic components in the first stage of the separation process (see Figure 15). When starting at a higher roll speed (180 rpm) the yield of final high-quality nonmagnetic product is higher than when starting at lower speeds, (170, 160, 150 and 140 rpm respectively). The next graph (Figure 16) shows the relative importance of feed rate. If the lower roll speed of 140 rpm is selected, the excessive weight removal in the first pass inevitably causes a loss of final nonmagnetic product, even if the starting feed rate is reduced. If the starting roll speed had been higher, the curves would have become much closer. The difference in yield would then be more directly related to slight differences in nonmagnetic product quality while minimizing the interference caused by nonselective entrapment (i.e., the highest quality and yield relationship would be achieved with the lowest feed rate). In other similar cases, there would be a noticeable difference only for feed rates higher than 4 tph/m. A few tests were performed by both our company and a South African mineral sands operation. Figure 17 confirms that reasonably close correlation was obtained, although we tend to use somewhat higher roll speeds for the first separation pass. This South African mineral sands operation has subsequently installed several of the largest roll separators available.

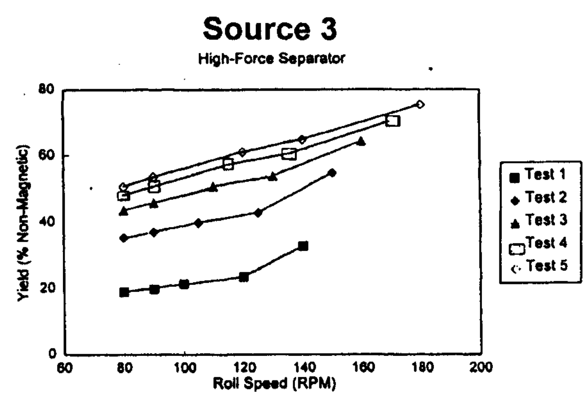

Figure 15. Effect of roll speed on yield

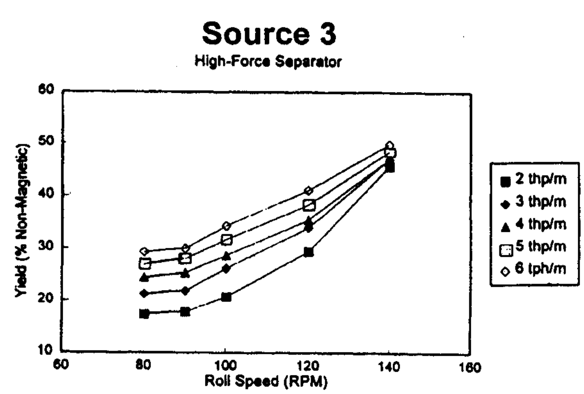

Figure 16. Effect of feed rate on yield

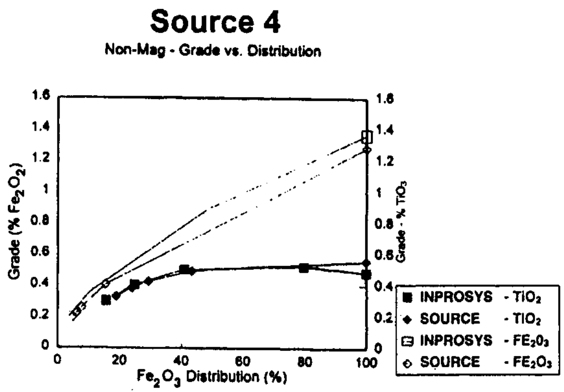

Figure 17. Correlation between a South African mineral sands operation and INPROSYS testing

Besides the magnetic design aspects on performance, it is important that the machine design enables reliable industrial plant operation and low maintenance. In this context, the emphasis should be on the thin belt operating life and the belt replacement method. Such factors have been reported previously in detail and are not repeated here[3,4,7]. It may be sufficient to say that the class 1 separator has consistently been the operators' favourite in all plants where a comparison has been conducted.

Until recently, there was no known case in the heavy mineral sands industry where the REM separators actually replaced the other separator types, as has occurred in other industrial mineral industries. No REM separator was used for a major primary process duty until late 1995. This year (1997), Westralian Sands Ltd will use the class 1 REM roll separators to replace a cross-belt separator plant for the first time.

Future developments

As the REM separators have found industry-wide acceptance in high-purity nonmagnetic material cleaning applications (e.g., glass and ceramic raw materials, zircon), as well as in high-grade magnetic material production (e.g., ilmenite, iron ore), the entire range of dry high-intensity applications is now open to application of such separators. In the wet processing area, the REM drum separators fill a need for mineral processing which falls between the low-intensity drum separators and WHIMS.

For large tonnage dry process requirements, large diameter roll and drum separators enhance the capacity per machine unit in proportion to the diameter. Such machines are already being introduced to the market. In comparing the process economics with super-conducting magnetic separators still under development, the current REM separator technology has the advantage. However, costs are decreasing in both areas, so the situation may change many years from now, although based on the presently known separator concepts it does not appear likely that the situation will be reversed.

For wet processing, the situation is different. For applications requiring very strong magnetic forces, the superconducting matrix-type separators (High-Gradient Magnetic Separator matrix) have several advantages. However, in the heavy mineral sands industry, the wet processing is almost exclusively used for magnetite removal and ilmenite recovery. The magnetic force requirement is modest, and continuous removal of the magnetic product is necessary to achieve the most economically attractive process. These conditions favour a continuously moving, matrix-carrying system through a magnetic zone (i.e., the vertical or horizontal wheel, also called 'carousel', high-intensity magnetic separators). Here, the rare-earth magnet technology is inadequate, as the operating air gap is too small to achieve high capacities. Other deficiencies cause matrix fouling or plugging problems. A new development using electromagnets may solve these latter problems.

For the next several years, the REM separators will continue to dominate the heavy mineral sands dry processing application. The REM drum separators will find more use in wet processing. However, unless a significant improvement in the REM separator magnetic force level is achieved, matrix-type separators will be the primary technology for this area.

Conclusions

Although it has taken the heavy mineral sands industry many years to adopt the REM technology in major processing areas, 125 production class 1 module units (many with 1.5 metre process width) were installed in the last couple of years for such duty. In contrast, nearly all previous REM separator installations in this industry were intended for corrections or modifications of existing flow sheet limitations.

Two South African heavy mineral sands companies, and Westralian Sands Ltd were the first to apply REM roll separators in major process application (ilmenite and zircon beneficiation). In all these cases, nearly all REM drum and roll separators available in respective countries were studied before the selection of the class 1 magnetic separator.

It is therefore possible to claim that the most advanced REM technology has now been fully accepted by the most progressive heavy mineral sands producers. Many more REM separators will find use in several new plants now under consideration or construction.

Acknowledgements

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