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A discussion of magnetic separation techniques for concentrating ilmenite and chromite ores

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Magnetic separation has long been used to upgrade and beneficiate a wide variety of industrial minerals. Advances in both wet and dry magnetic separators over the years has broadened their use, and questions are often raised about which separation technique or equipment type is most appropriate for a particular operation.

This paper will provide a brief look at existing magnetic separation technologies, and discuss their potential advantages and disadvantages when applied to heavy mineral applications. Relevant case studies for the separation of ilmenite and chromite are then presented. The process development efforts undertaken for each case are described, and the rationale for selecting appropriate magnetic separation technology is explained. The nature of the material being treated must clearly be understood, knowledge and access to testing the best separation technologies is required, and careful process development and economic evaluations are a must.

As is shown in the case study discussions, it is imperative that these principles drive the separation technology selection and placement, rather than looking at typical or existing similar flowsheets as rules.

As examples, the ilmenite tailings case study presented in this paper shows how advances in technology have allowed for increased recovery of -45 μm ilmenite by utilizing a multi-stage SLon® wet magnetic separator circuit equating to an additional 30 000 tons of ilmenite produced per year. The virgin chromite case study presented shows that through careful testing and circuit design efforts using RED technology, a 20% increase in overall chromite recovery was achieved over previous demonstration work.

Introduction

Minerals separation based on magnetic susceptibility differences in particles is accomplished wet or dry, at various intensities and in different basic machine configurations. The following types of industrial magnetic separators can be found in a modern mineral sands plant:

- Wet high-intensity electromagnetic separators (WHIMS)
- Wet low-intensity drum separators (LIMS)
- Dry high intensity induced roll magnetic (IRM) separators
- Dry low intensity drum-type separators or 'scalper' magnets
- Dry high-intensity rare-earth drum (RED) separators, and
- Dry high-intensity rare-earth roll (RER) separators

Figure 1 depicts the basic magnetic separation technologies now available in the marketplace in terms of field intensities and modes of processing. LIMS and scalper magnets are not detailed in this paper.

The selection of magnetic separation technology depends on many processing factors, including particle size, and the specific assemblage of minerals and grades as well as their corresponding magnetic susceptibility. Additionally, production and marketing factors must also be considered, i.e. is ilmenite production linked to rutile and zircon production, is the ilmenite saleable or is it waste, are further downstream processes necessary to bring products to a marketable quality, etc.?

Prior to discussion of separator selection in specific circumstances, it is beneficial to understand the general rationale for placing different types of magnetic separators in mineral sands applications.

Common practice for magnetic separator placement in mineral sands applications

Wet vs. dry

As a rule of thumb, operations look to reduce drying requirements for obvious cost implications. Employing wet magnetic separation early in a process can greatly benefit an operation if a low-grade final tailing, or a clean marketable product, can be produced, since it alleviates both drying and dry storage costs.

While WHIMS use can be advantageous, a common drawback of conventional designs is entrapment of non-magnetics in the magnetics product, particularly when treating finer particles. This shortcoming has been addressed with the SLon® vertically pulsating high gradient magnetic separator (VPHGMS). The advent of the SLon® machine has extended the use of WHIMS into finer applications previously untreatable by conventional WHIMS or conventional gravity concentration. As an example, recovery of hematite and ilmenite fines with SLon® technology is now practised widely throughout China. It is also being piloted by many mineral sands producers worldwide, both to replace prior art WHIMS and as a potential intermediate step between traditional WHIMS and dry magnetic separation.

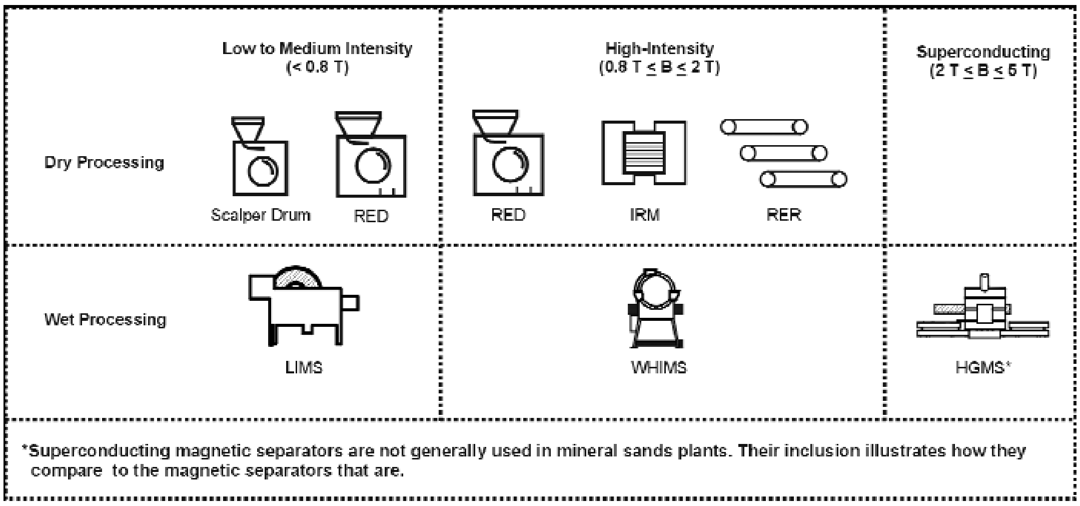

Figure 1. Comparison of magnetic separation technologies

Dry magnetic separators, including both drum and roll types, generally offer far more precise separations than wet magnetic separators. Dry magnetic separation is more controllable since the separation medium is air rather than water. Separating particles from one another is naturally easier without having to fight drag forces created by water. This creates a distinct advantage to using rare-earth dry magnetic separators: the ability to produce a variety of TiO_2 products rather than a simple mag/non-mag split. Additionally, rare-earth dry magnetic separation circuits are typically lower in capital and ongoing maintenance costs, and are less complicated to operate than WHIMS.

Rare-earth drum vs. rare-earth roll

A RED is most often used to separate two or more paramagnetic minerals into separate finished products (or semi-finished products for further polishing) in the early stages of a dry separation process flowsheet. Additionally, a RED typically operates at higher unit capacity than a RER separator.

A RER is more commonly applied to residual streams after removal of the more highly susceptible magnetic minerals such as ilmenite, chromite and garnets. A RER is also commonly used for recovery improvements and final cleaning of high-value products, like rutile and zircon, where their higher field strengths are required if proper separation is to occur. For example, the recently developed Outotec® high-efficiency (HE) RER is now being employed in finer zircon-rich applications, and has shown up to a 3% increase in efficiency over conventional RER and IRM units (Elder, 2006).

Induced-roll magnetic separators

IRM separators have historically been used in mineral sands processing. Some remain in various mineral sands circuits but RER separators are rapidly replacing them. The RER allows mineral processors to get over 50% greater capacity per unit operation over IRM separators. This allows for smaller footprints without compromising performance, which equates to substantially reduced costs per ton treated. RER separators offer a reduction of nearly 60% operating costs compared to IRM separators, and the capital cost of a RER is about 30% less than an IRM.

Typical ilmenite process flowsheet

Figures 2a and 2b show basic examples of flowsheets for ilmenite processing including wet and dry magnetic separation.

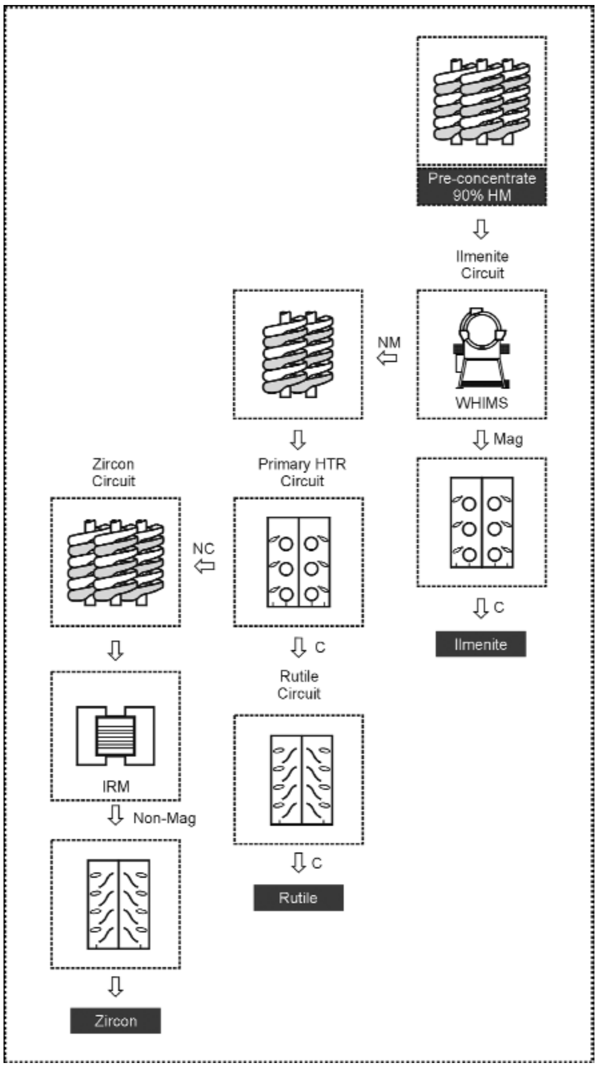

Figure 2a. Ilmenite flowsheet using WHIMS
(Elder, Kow, 2005)

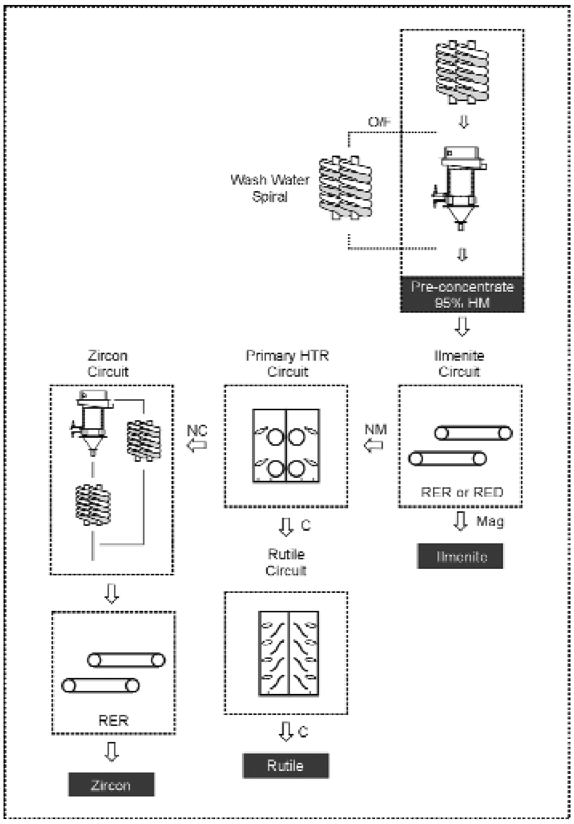

Figure 2b. Ilmenite flowsheet using dry magnetic separation (Elder, Kow, 2005)

In Figure 2a, the WHIMS is used after conventional gravity concentration to remove a magnetic stream that can be upgraded easily to finished-product ilmenite. The resulting non-magnetic fraction is then further upgraded by gravity concentration, and followed by conventional dry separation techniques to create the higher value zircon and rutile products.

In Figure 2b, the wet process consists exclusively of gravity concentration followed by a dry plant for fractionating the HMC into various products. In some instances, where high levels of magnetic contaminants exist in the assemblage, electrostatic separation is carried out as the first dry processing stage, followed by magnetic fractionation using a combination of RED and RER separators to produce the various grades of titanium-mineral products.

Typical chromite process flowsheet

In some cases, chromite concentrates can be produced by wet gravity concentration alone. In other chromite beneficiation processes, magnetic separation by RED is an essential polishing step.

Figure 3 shows a typical flowsheet for upgrading chromite where gravity concentration is followed by dry magnetic separation.

Case studies

Several case studies are presented that describe the testing and flowsheet development work that enabled proper magnetic separation technology selection and flowsheet configuration.

Case Study 1: Dry magnetic separation of ilmenite before electrostatic separation

The deposit for Case Study 1 was a typical aeolian reworked mineral sand deposit with a heavy mineral assemblage of ilmenite, rutile, zircon, sillimanite, monazite, magnetite and other minor minerals.

In Early path finding test work of small samples indicated that a majority (~70%) of the ilmenite could be recovered as finished product by using RED magnetic separators as the first separation step—rather than electrostatic separation as is most common.

To validate this important finding, a single stage magnetic fractionation, using an Outotec® RED equipped with multi-tray collection boxes, was performed. The feed was generated by gravity concentration to >95 % HM and NaOH-based attrition scrubbing. The results are summarized in Table I, substantiating the earlier findings. The results indicate that total ilmenite product from this unit operation would amount to 66% weight of the HMC feed, and the corresponding quality was well within product specifications.

The early tests shaped the larger pilot testing flowsheet, with the essential elements as follows:

- Scalping by low-intensity drum magnet to remove ferromagnetic materials. This magnetic stream was combined with the primary ilmenite product

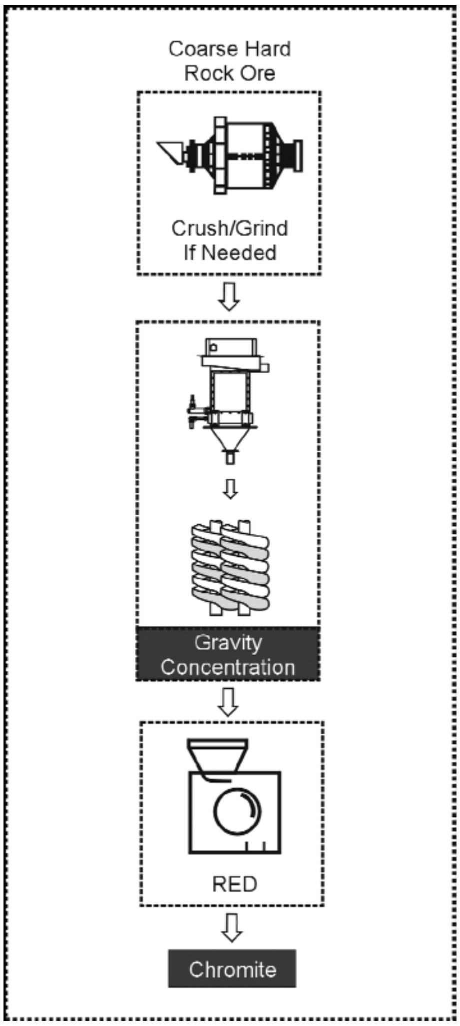

Figure 3. Typical chromite flowsheet

Table I
RED Fractionation of HMC

Products Attrition scrubbed HM		Yield (%Wt.) 100.00	% TiO_2	% SiO_2	% ZrO_2	% Al_2O_3
Mag	Tray 1	1.7	53.29	0.33	0.02	0.46
	Tray 2	3.0	53.15	0.32	0.02	0.043
	Tray 3	2.5	53.05	0.36	0.02	0.44
	Tray 4	1.7	53.16	0.34	0.01	0.42
	Tray 5	0.6	53.25	0.36	0.02	0.47
	Tray 6	0.2	53.26	0.45	0.02	0.47
	Tray 7	22.2	52.91	0.53	0.03	0.42
	Tray 8	22.5	52.76	0.59	0.04	0.46
	Tray 9	8.3	52.68	0.69	0.05	0.45
	Tray 10	2.6	52.76	0.60	0.05	0.45
	Tray 11	0.8	52.84	0.50	0.05	0.42
	Tray 12	0.2	52.81	0.50	0.05	0.41
Total mag		66.3	52.86	0.54	0.04	0.44
Mids		6.8				
Non mags		27.0				

- Magnetic fractionation by RED to recover 50 to 60% weight of the feed as a primary ilmenite product; requiring no electrostatic pretreatment
- Recovery of residual ilmenite in the RED non-magnetic fractions as secondary and tertiary ilmenite products via retreatment with higher intensity RER followed by cleaning with high tension roll (HTR) separators
- After ilmenite removal, the final non-magnetic stream was subjected to traditional processing methods to generate rutile and zircon products.

A simplified process flowsheet for the ilmenite circuit products is depicted in Figure 4.

A WHIMS was not recommended for this application for the following reasons:

- The presence of garnet and monazite contaminants in the assemblage required electrostatic separation to properly upgrade a portion of the ilmenite product
- Three separate ilmenite products were desired, requiring the flexibility and control that can only be accomplished with dry separation methods
- While rutile and zircon are important products, the production of on-specification ilmenite products was critical to overall project success
- Dry magnetic separation simplified the flowsheet and saved capital and operating costs.

Case Study 2: Ilmenite tailings recovery using WHIMS

The hard rock deposit for Case Study 2 consisted of iron and titanium bearing minerals as well as vanadium and other gangue minerals. The main goal was to recover the abundant magnetite and ilmenite components; however, ilmenite recovery was problematic, hovering in the 17–20% range, because sufficient technology for recovery of the significant values in the -45 μm fraction was not initially available. (Xiong, 2006)

Studies were performed to upgrade the operation. Test work revealed that the recently developed SLon® WHIMS was the key to enabling the operation to process this fine fraction. The plant was upgraded with SLon® WHIMS technology to process the –45 μm stream. The result was an overall doubling of TiO_2 recovery at an average concentrate grade of 47.5% TiO_2. Additionally beneficial, the SLon® discarded most of the gangue minerals and slimes prior to flotation so less than one quarter of the initial mass feed entered the flotation circuit.

While the SLon® application was a great improvement, the tailings still contained approximately 7% TiO_2. Further testing led to the implementation of a tailings reprocessing circuit to gain additional recovery. Again, the upgrade employed SLon® WHIMS technology. A simplified flowsheet of the final tailings retreat circuit is shown in Figure 5.

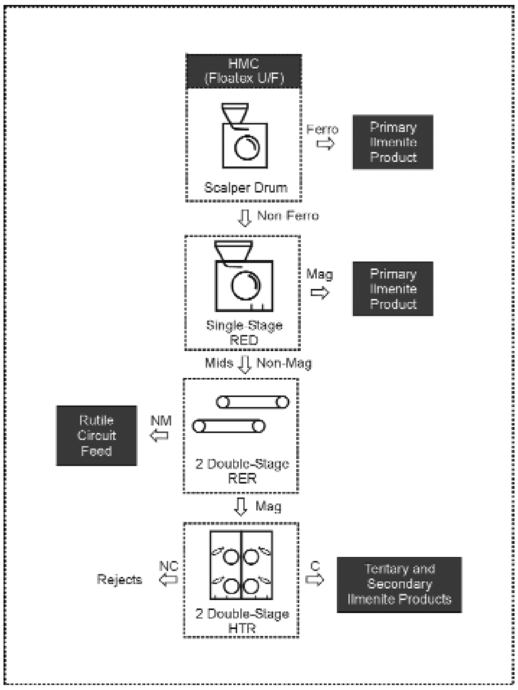

Figure 4. Simplified flowsheet for Case Study 1

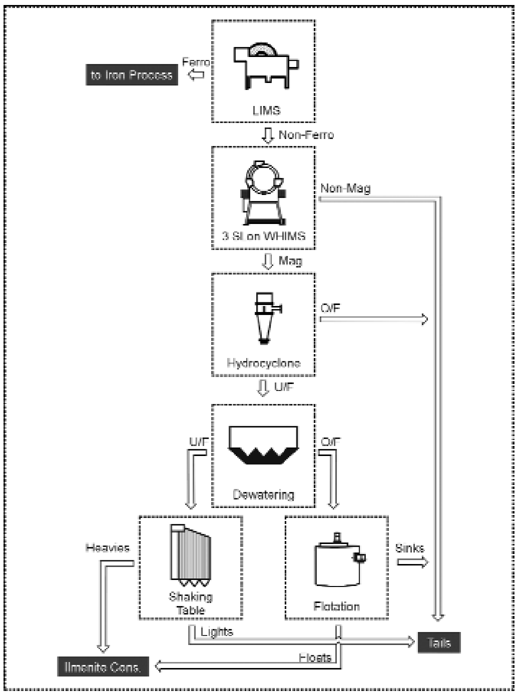

Figure 5. Simplified flowsheet for Case Study 2

Low-intensity magnetic separators are utilized to recover any remaining magnetite. The LIMS is followed by a rougher stage of two SLon®-1500 magnetic separators. A third SLon®-1500 magnetic separator is then applied to recover ilmenite in a cleaning stage.

Combined, the three SLon®-1500 separators discharge 81.5% of the mass fraction to the final tailings at very low cost, with only 18.50% of the plant head feed moving forward in the process. The tailings retreat circuit produces a product grade of 47.66% TiO_2. Recovery of the ilmenite is 31.19%, which equates to an additional 30 000 tons ilmenite concentrate annually for the operation.

Dry magnetic separation was not recommended for this application for the following reasons:

- Flotation is used throughout the initial flowsheet and the tailings retreat circuit, so additional drying costs would be present
- Ultra-fine materials are difficult to process with dry magnetic separation
- No rutile or zircon co-products were present; hence no dry processing was necessary.

Case Study 3: Separation of chromite using traditional dry separation techniques

Case Study 3 was based on a heavy mineral sands deposit containing chromite, garnet, zircon and titanium bearing minerals.

Initial studies identified a problematic magnetic susceptibility overlap between the titanium bearing minerals and the chromite. For this reason, early test work had defined an overall saleable chromite recovery limit ranging from 60–70%. The following case study focuses on the process development testwork specifically targeted at increasing chromite recovery without compromising finished product quality.

Gravity concentration was carried out utilizing a combination spiral and Floatex® density separator circuit, for optimal preconcentration, followed by an attrition scrubbing stage. Due to the specific assemblage, using magnetic separation alone would produce a combination product of magnetite, titanium-bearing minerals, chromite and garnet. For this reason, the use of WHIMS was ruled out early. After drying, HTR separation was used to create a conductor fraction containing mainly magnetite, titanium bearing minerals and chromite.

Extensive small-scale testing was carried out to determine the best magnetic separation route for increasing chromite recoveries, resulting in a large number of RED and RER flowsheet configurations being evaluated. Ultimately, a multi-stage scalper/RED circuit was defined to effectively scalp magnetite and increase chromite recovery approximately 20% over the previous work. The mid-range intensity of the drum allowed for improved selectivity in the chromite and ilmenite separation, while also allowing higher rate processing than the RER.

The first drum pass is used solely to remove the magnetite fraction. The second two RED stages, arranged in a middling-retreat configuration, produce the chromite and titanium-rich products. Unique to this chromite magnetic circuit design is that the chromite product is comprised of the non-magnetic streams from the second and third RED stages. Given this fact, it is important to note that the preceding HTR electrostatic step is critical to avoid possible non-conductor contamination of the chromite product. The basic flowsheet is illustrated in Figure 6.

Assays from this portion of the circuit are overviewed in Table II.

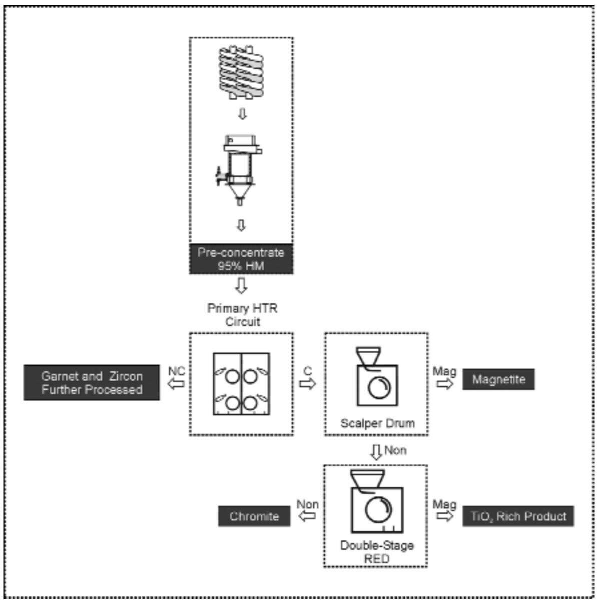

Figure 6. Simplified flowsheet for Case Study 3

Table II
Conductor/magnetics circuit assay overview

Circuit	Product	Total Wt.%	Cr_2O_3			TiO_2			$ZrO_2 + HfO_2$		
			%	Unit Dist.	Tot. Dist.	%	Unit Dist.	Tot. Dist.	%	Unit Dist.	Tot. Dist.
From HTR To RED	Conductors	60.0	36.8	100	87	8.2	100	84	0.0	100	0
Scalper mag	Mag	3.0	6.9	1	1	29.8	19	16	0.1	100	0
	Non-mag	57.0	38.4	99	86	7.0	81	68	0.0	0	0
RED mag 1	Mag	9	5.4	3	2	35.2	43	29	0.1	0	0
	Middling	11	6.6	4	3	36.1	53	36	0.1	0	0
	Non-mag	37	44.2	93	80	0.8	4	3	0.0	0	0
RED mag 2	Mag	0	12.0	0	0	29.0	3	1	0.0	0	0
	Middling	4	29.7	28	1	10.4	84	30	0.0	0	0
	Non-mag	7	46.4	72	2	1.0	13	5	0.0	0	0
Total		60.0	-	-	82	-	-	76	-	-	0

Note: For this deposit, Cr_2O_3 X ~2.14 = chromite

The HT conductor fraction contained 87% of the head feed Cr_2O_3 units, and of the head feed, 82% of the Cr_2O_3 was recovered in this rare-earth drum circuit versus the 60–70% Cr_2O_3 recovery by prior test work. Of the recoverable Cr_2O_3 units in the magnetic separation stage alone, the combined Cr_2O_3 recovery was 95.9% with an average product quality of 44.5% Cr_2O_3 (95.2% chromite).

A WHIMS was not recommended for this application for the following reasons:

- The WHIMS was tested previously and resulted in low chrome recovery
- The WHIMS removed the magnetic non-conductors along with the magnetic conductors so an electrostatic step would still be required
- The use of a WHIMS would not have saved in drying costs.

Case Study 4: Reclaimed chromite sands using RER

The feed material for Case Study 4 was chromite bearing sand material reclaimed from old foundry dump areas. The existing operation suffered from several separation and other process issues related to the post-use characteristics of the material. Among these issues were low chromite recoveries in the existing rare-earth drum circuit. The magnetic separation was complicated by the variable presence of magnetic slag impurities that had a susceptibility overlap with the valuable chromite. This caused unacceptable finished product qualities.

In order to maintain product quality, machine adjustments were being made during operation, which drove chromite recoveries down to very low levels. Operation of the magnetic separation circuit was very conservative to ensure chromite quality was acceptable for shipment, but even in this case Cr_2O_3 values rarely exceeded 40%.

A number of tests were carried out with the typically problematic magnet circuit feeds. Since the existing operation already utilized RED separators, and chromites are typically treated in this manner, early testing focused on benchmarking the plant performance with lab RED testing. Generally, the lab testing results were slightly better than plant performance, but not to a marked extent. This poor performance led to additional characterization of the feed material revealing the post-use feed material issue of magnetic slag contaminants. Lift-roll lab magnetic fractionation of the sample clearly illustrated that the slag impurities overlapped with some of the quality chromite. This work also uncovered that some of the chromite should have been considered unrecoverable because the existing scrubbing regime was not removing surface coatings and so rendering them non-magnetic. There was, however, a reasonable portion quality chromite, void of impurity, noted at very high intensities that could be produced.

Though magnetic separation of chromite is typically performed on a RED, the characterization data led to additional testing on the higher intensity RER.

After a number of tests, a workable solution was discovered when using the Outotec® RER with a high roll speed. The simplified flowsheet is shown in Figure 7. The first pass was run at 400 rpm, producing a magnetic fraction containing magnetite and the magnetic slag material. The next two passes were run at 300 rpm, with overall weight recovery to the combined 2nd and 3rd pass magnetic fractions of ~50%. This combined magnetic product graded 45.9% Cr_2O_3 (~98.3% chromite mineral), which was an increase of 6% Cr_2O_3. The corresponding Cr_2O_3 recovery nearly doubled to 67%. Test results are shown in Table III.

The use of the RER for the operation, running at high roll speeds, far outperformed the RED in both product grade and overall recovery. Capitalizing on the combination of the higher field intensity of the RER, and high centrifugal force, enabled clean separation of the chromite away from the magnetic slag impurity.

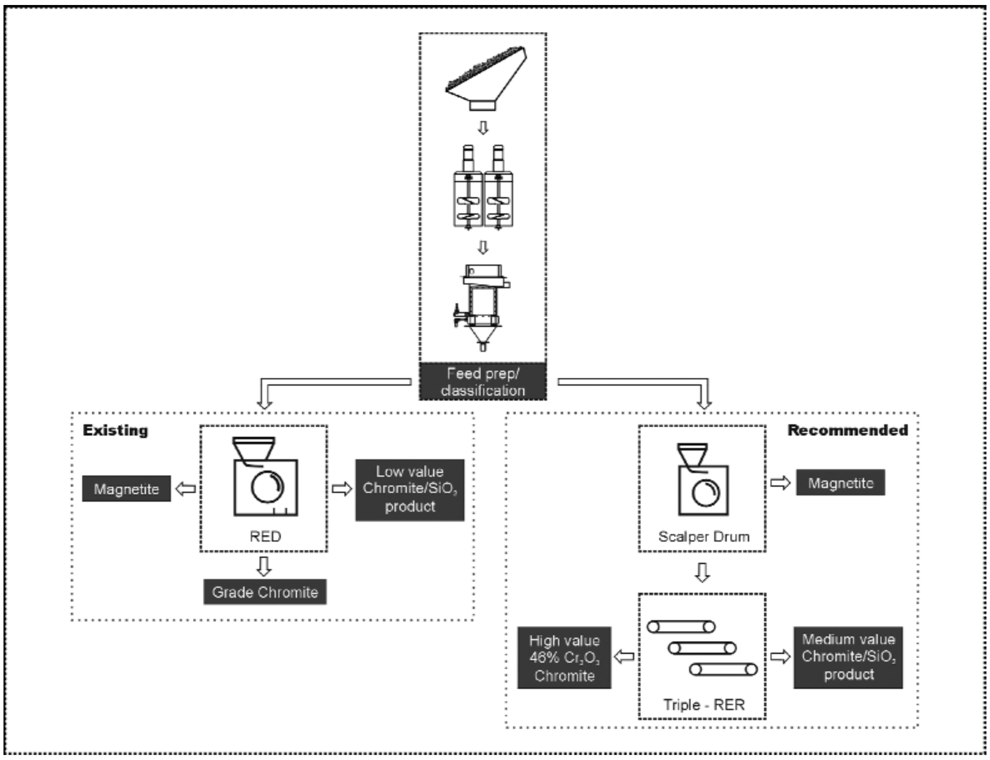

Figure 7. Existing vs. suggested flowsheet for Case Study 4

Table III
RER test results

RER 4:1.3 Roll 1.0 mm Belt 5 tph/1.5 m				
	Wt.%	%Cr_2O_3	% Recovery	Speed (rpm)
Feed	100.00	35.3	-	-
Mag 1	16.1	20.3	9.3	400
Mag 2	39.1	**45.8**	**50.8**	300
Mag 3	12.3	**46.4**	**16.1**	300
Non-mag	32.6	25.8	23.8	

A WHIMS magnetic separator was not recommended for the following reasons:

- The overlapping magnetic susceptibility of the feed required the use of more selective magnetic separation, i.e. rare-earth roll using high centrifugal force. A wet magnetic separator would not allow for the use of centrifugal force and would have produced the same problems as the initial drum
- The drum was already in place; hence the material was already being processed dry.

Conclusions

There are several magnetic separation technologies available for inclusion in modern minerals sands processing flowsheets. Each basic technology, along with potential advantages and disadvantages, has been reviewed for typical applications in minerals sands processing. However, the specific case studies, purposefully included in this paper, demonstrate that selection of magnetic separation technology is not always straightforward, but rather an emphasis must be placed on careful process development efforts to ensure optimum flowsheet design.

One case study showed that, in some cases, RED technology can be used as the initial dry processing step to make finished products, thereby reducing and simplifying downstream equipment requirements. The fine ilmenite recovery study showed that the new SLon® wet magnetic separator, when placed in a tailings circuit, produced an additional 30,000 tonnes of ilmenite per year, from a stream considered too fine to treat with conventional WHIMS. One chromite application testing program demonstrated that equipment selection and retreatment configuration led to a unique multi-stage RED circuit that was able to increase chromite recovery by 20% over prior studies. Lastly, in a reclaimed chromite service, an RER was found to be an improvement over an existing, and typical, RED circuit with dramatic improvements in both grade and recovery.

In closing, Table IV summarizes magnetic separation technologies for various applications. These suggestions, along with critical validation through process development testing, can be used to guide magnetic separation technology selection to ensure optimum overall flowsheet design.

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Table IV
Magnetic separator selection guide

Criteria	Roll separator	Dry drum separator	SLon WHIMS
Ferromagnetic material (magnetite, tramp iron)	Scalper model (low strength) with long-lasting thick belt	Small amount tolerated (<1%), using release bar	Needs to be scalped first by LIMS
Highly paramagnetic material (ilmenite, garnet)	Moderate-strength with high capacity, thick long-lasting belt	High-strength, release bar required, high feed rate, less separation sharpness than roll	High efficiency if wet process is desired
Moderately paramagnetic (biotite, leucoxene, monazite)	High efficiency, higher grade and recovery compared to electromagnets.	No use	High efficiency if wet process is desired
Weakly paramagnetic (muscovite, amphiboles, pyrite) Cleaning of quartz, feldspar, zircon, rutile	High efficiency, higher grade and recovery compared to electromagnets	No use	Moderate efficiency
Operations and maintenance	Low attendance. Belt change easy.	Minimal operator attendance. Replacing drum shell requires qualified shop work	Minimal attendance, significantly less than a horizontal WHIMS configuration.
High capacity	150 mm versions providing 1.5x capacity of 100 mm roll	Very high capacity with 610 mm diameter drums. Larger drums are also available	80–150 tph with largest model 2500
High temperature	+120°C if needed	Up to 100°C	Not applicable
Process control	Wide range of parameters, great control flexibility	Moderate range of adjustments	Moderate range of adjustments