Fine chrome beneficiation and reverse PGM upgrade of existing slimes with vertical ring WHIMS technology

W.P. Slabbert

Multotec Process Equipment, Johannesburg, South Africa

The main differences between a vertical and a horizontal ring WHIMS machine are described. Four UG2 samples with P_{80}=100 µm were delivered from four different slimes dams on the western limb of the Bushveld Complex containing gravity separation tailings. A pilot-scale Longi-Multotec LGS 500 vertical ring WHIMS unit was successfully used to upgrade chromite by 6–14% with a recovery of 44–62% at 0.4 T, and by 4–6% with a recovery of 55–72% at 1.3 T. A horizontal ring WHIMS of comparable size was not available for testing. The broad range of grades and recoveries are believed to result from increased viscosity effects attributed to unreacted PGM flotation chemicals present in some samples. The viscosity effects were less pronounced at higher background magnetic field intensities, and this needs more investigation. The reverse upgrade of PGMs in the WHIMS tailings stream, through chromite removal to the magnetic concentrate stream, resulted in PGM grades of up to 6.5 ppm at a recovery 50%, which could make it economical to re-float this material, thereby increasing revenue for existing operations.

INTRODUCTION

Chromite $(Fe,Mg)(Cr,Al)_2O_4$ is a paramagnetic mineral that occurs as a gangue mineral associated with platinum group metal (PGM) orebodies in the western limb of the Bushveld Complex. Chromite grades vary between 3–5% in the Merensky Reef and the Platreef, and 5–15% in the UG2 reef (Engelbrecht, 2012).

The chromite could adversely influence flotation of the PGM minerals, and recent flow sheet configurations use gravity separation spiral circuits to remove chromite before flotation. This can be done safely without losing PGMs to the spiral heavy concentrate, since the PGM-bearing silicates are normally liberated from the chromite for UG2 material (Engelbrecht, 2012). Post-flotation spiral circuits are typically installed to separate the chromite – now the valuable product – from the PGM-stripped silicates which are no longer economic to float, even though PGMs might still be present in concentrations of less than 5 ppm.

A large number of slimes dams exist in the area with typical chromium and PGM grades of 10–25% and 1–5 ppm respectively (estimates from experience with the samples tested as presented in this paper).

Even with desliming and advancements in spiral diameter, pitch and slope, like in the HX5 spiral, these spirals are believed to be limited in effectively treating particles finer than 100 µm. The post-flotation particles are typically 5–300 µm (Engelbrecht, 2012).

There are vast amounts of fine chromite available in the slimes dams that currently cannot be effectively recovered. Beneficiation of this material holds potential economic benefits of cost savings, since mining, milling, and separation have already been done. A spin-off advantage could be the reverse upgrade of the far more valuable PGM minerals, where flotation could be considered feasible for streams with PGM concentrations of more than 6 ppm.

Wet high-intensity magnetic separation (WHIMS) is able to recover 5 µm haematite particles with 50% efficiency (Forssberg and Kostkevicius, 1982) and can also be applied to other paramagnetic minerals such as chromite.

LITERATURE SURVEY

Chromite Recovery with WHIMS

Guney *et al*., as referenced by Murthy *et al*. (2011), used WHIMS and column flotation to beneficiate chromite tailings from a Turkish gravity separation circuit with a particle size 83% smaller than 100 µm. The tailings were successfully upgraded from 20–22% wt.% Cr_2O_3 to 45–48%, with an overall recovery of 60–65%.

Tripathy *et al*. (2013) reported chromite upgrades from 26.4% to 40.1% Cr_2O_3 with 37.6% recovery using WHIMS on an Indian chrome plant tailings stream.

Background Field Intensity *versus* Field Intensity in the Matrix

The magnetic field intensity generated by an electromagnetic coil wrapped around a core is carried to the area of separation (the matrix) by a yoke of suitable material; typically mild steel. The shape, geometry, and electromagnetic properties of the matrix material affect the way the background field intensity is concentrated in the matrix, which will result in different field intensities and gradients experienced by the particle – ultimately affecting the force applied to the particle.

In some vertical ring WHIMS machines the background intensity can be as high as 1.3 T. This intensity is sufficient to allow a concentration factor of 2 in the matrix (where the background intensity is 0.5 or 1.0 T, the intensity in the matrix would be 1.0 or 2.0 T respectively) – except for the highest intensity setting of 1.3 T where the concentration factor is only 1.9 and the intensity in the matrix 2.5 T. A magnetic intensity diagram of the field intensity distribution can be seen in Figure 1.

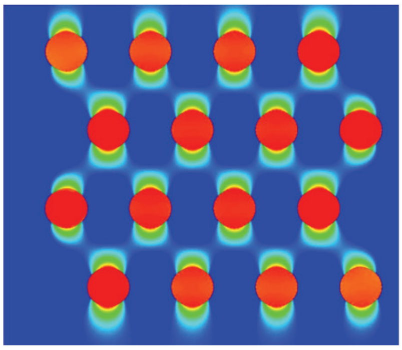

Figure 1. Magnetic field Intensity of a typical vertical ring WHIMS matrix showing a background intensity (dark blue) of 1.0 T and field intensity concentration of up to 2.0 T (red), with intermediate intensities of 1.7 T (yellow), 1.35 T (green), and 1.15 T (light blue).

Horizontal ring WHIMS models can generate up to 1.0 T (maybe more). The field intensities on the surface of the profiled plate matrix are expected to be of the same order of magnitude as in the vertical ring WHIMs at 1.7 T.

Comparison of Vertical and Horizontal Ring WHIMS

All WHIMS machines (or high-gradient separators) have the following major parts:

- A feed arrangement (with or without oversize protection) that presents the feed slurry to the separation matrix, and an associated level control system
- The rotor or ring that contains the separation matrix which governs the separation method, the rotor's drive system, and product collection
- The matrix, where separation occurs on a specific design surface comprising cylinders, rods, profiled plates, steel wool, or other surfaces
- The yoke, which is generally a sufficiently large piece of mild steel that 'conducts' the magnetic field from the coil to the rotor, where it is presented in a proprietary field distribution
- The magnetic coil(s) that generates the magnetic field, and an associated heat exchange system
- A product stream collection arrangement with a wash water system to wash the products from the matrix
- Control panel.

Figure 2 and Figure 3 depict the layout of the major components of vertical and horizontal ring WHIMS machines.

Feed Arrangement and Level Control

The vertical ring WHIMS is fed on both sides of the rotor via two feed inlets. Various oversize protection devices can be installed at the top of the inlets. The chambers are joined again deeper in the machine in the slots in the yoke and the slurry-containing tank (Figure 2), so reasonable imbalances between the two incoming feed rates are eliminated in the common tank. It is also possible to install level control on the visible overflow weir of the machine to control the feed and/or product discharge rate. The slurry bath provides some buffering against fluctuations in the feed, which promotes ease of operation. The slurry bath also offers a buffer against incoming flow directly impacting on the matrix, which could generate turbulence and shear, resulting not only in the removal of non-magnetic material entrapped in the magnetic concentrate layer, but also possibly the misplacement of magnetic concentrate to the nonmagnetic product stream.

The horizontal ring WHIMS has eight feed points. A level, well-designed and monitored feed distributor is required to feed all feed points at equal rates to prevent over- or under loading of individual points, which will result in underperformance of a feed point with regard to grade and recovery. The pulp distributor outlets feed into eight boil boxes, which may contain oversize protection trash screens. Manual level control between feed rate and rotor speed is required, especially when fluctuating feed conditions are experienced, against which the top-in bottom-out feed arrangement offers no buffer. The feed impacts directly on the matrix, where turbulence and shear rates are high and could result in effective washing of entrapped nonmagnetic particles, but in the extreme case may also result in loss of the desired magnetic material.

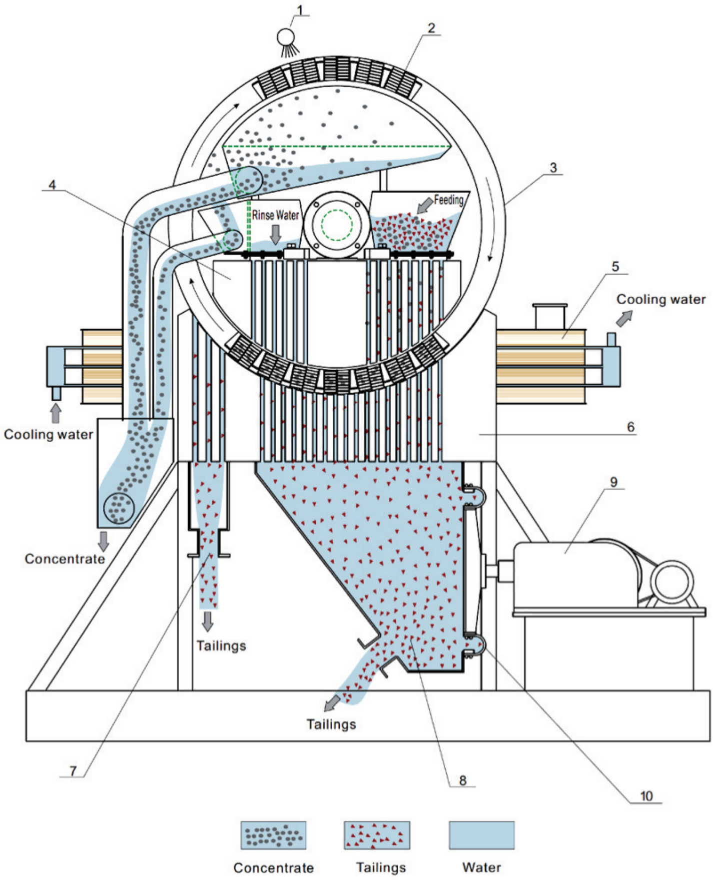

Figure 2. General cross-sectional layout of a vertical ring WHIMS showing (1) wash water system, (2) matrix boxes making up the matrix, (3) rotor rotating in the vertical plane, (4) magnetic yoke north pole, (5) magnetic coil, (6) magnetic yoke south pole, (7) middlings product, (8) tailings product, (9) pulsation system drive, and (10) pulsation membrane.

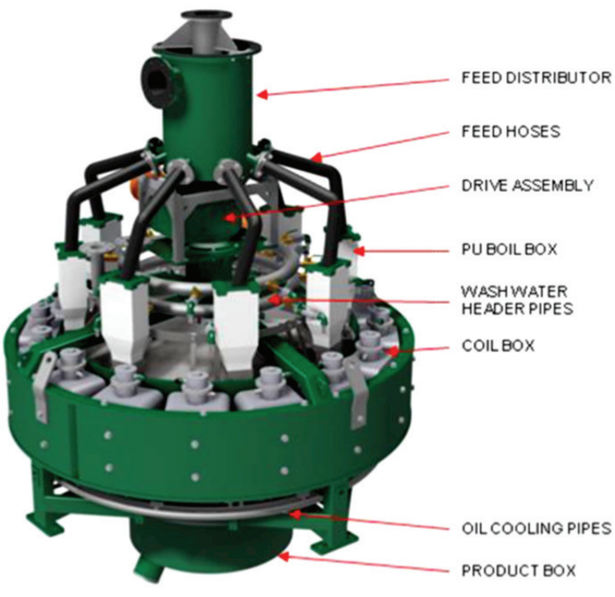

Figure 3. General layout of a horizontal ring WHIMS.

Ring Orientation, Drive System, Method of Separation, and Product Collection

The vertical ring rotates in the magnetic zone between the north and south poles of the yoke. The matrix is charged by the magnetic field and magnetic particles attach to the matrix. Magnetic particles are carried sideways with ring rotation and finally washed out at the top of the machine, while nonmagnetic particles pass through the matrix and out at the bottom. The slurry bath ensures a fully wetted matrix, which provides water as medium for movement and also protection against shear due to incoming slurry, which can contribute to misplacement of magnetic material from the matrix elements and adversely affect the recovery of magnetic minerals. A rubber membrane pulsator (Figure 2) acts on the slurry to keep the solids in suspension and impose a scrubbing mechanism to increase product grade and recovery, by allowing more time for interaction with the matrix. This pulsation is adjustable and independent of feed rate, allowing scope for optimization.

The horizontal ring is fed in a top-in bottom-out configuration into each of the eight magnetic zones (Figure 4). It is important that the ring speed is adjusted in accordance with the prescribed flow rate to ensure proper wetting of the matrix. Each feed point has three associated product collection boxes (thus 24 in total) with adjustable splitter blades for grade and/or recovery optimization. The lack of a slurry-containing bath makes the unit sensitive to changes in feed rate, but does allow high shear forces in fast flowing fluid that assist with cleaning of any entrapped nonmagnetic particles on the profiled plate surface.

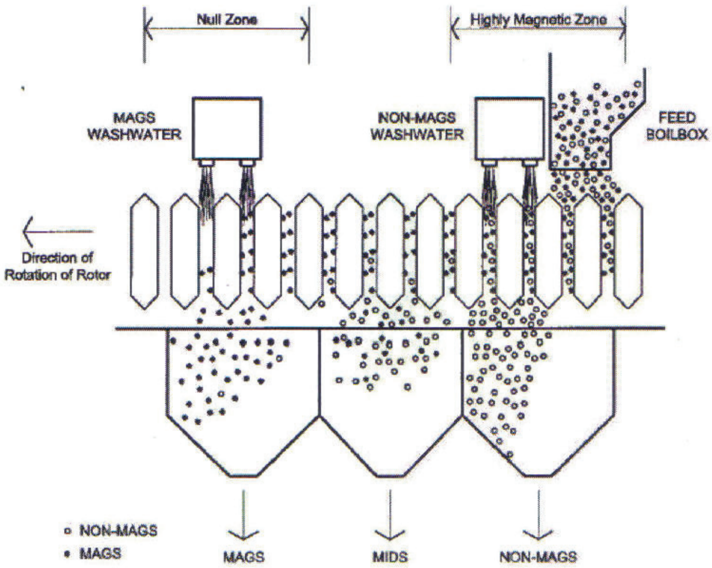

Figure 4. Separation principle of the horizontal ring WHIMS indicating one of the eight feed points with the associated nonmagnetic, middlings, and magnetic products.

Matrix Construction

The vertical ring matrix consists of individual matrix boxes fixed in place with a bolt-in wedge that can be replaced *in situ*. Each matrix box has tens or hundreds (depending on the machine model, size, and matrix specification) of matrix rods (or other innovative elements) providing the separation surface area.

The horizontal ring WHIMS rotor is installed in the middle of the machine as a complete unit with all of the profiled plates (typically 224) welded in place, hindering maintenance operations.

Magnetic Coil(s) and Cooling System

The vertical ring WHIMS uses one pancake of turned wire in a horizontal nonmagnetic stainless steel housing. Two, three, or four pancakes can be stacked and welded on top of each other to make up a coil that can generate background intensities in the matrix of 0.6, 1.0, and 1.3 T, respectively. Channels between the pancakes allow cooling water to be pumped through.

The horizontal ring WHIMS uses three smaller wire pancakes in a stainless steel housing to make up one coil. Oil is pumped through the coil for cooling purposes; in some models the coils are air-cooled. There are a total of 16 coils that generate up to 1.0 T background magnetic intensity in the matrix.

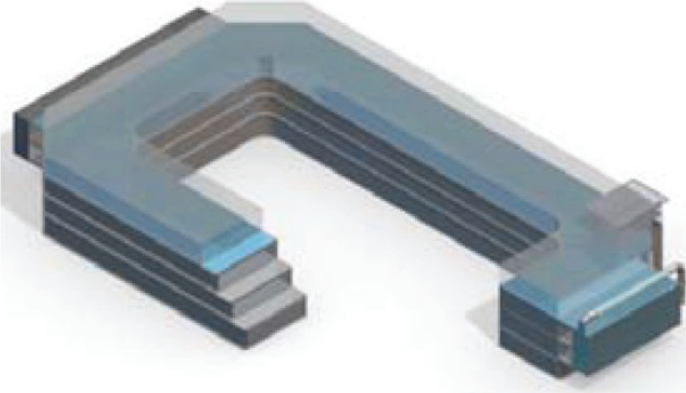

Figure 5. A vertical ring WHIMS, four-pancake coil capable of generating 1.3 T background intensity in the matrix.

Figure 6. Two of the 16 coils making up the electromagnet of a vertical ring WHIMS unit capable of generating 1.0 T background intensity; note the oil outlets at the top of the coil box.

EXPERIMENTAL

Test Equipment and Parameters

Test runs were conducted using a Longi-Multotec LGS 500 pilot-scale vertical ring WHIMS with associated feed sump and pump with valve-controlled recycle and agitator, header tank with two-way distributor, and control panel. A pilot-scale horizontal ring WHIMS of comparable size was not available for testing.

Magnetic field intensity was set at 0.4, 0.7, 1.0, and 1.3 T. Chromite feed grades were not controlled and the samples were tested as received. The solids feed rate was controlled around 80–120 kg/h, which is the mean of the machine capacity (50–250 kg/h). Solids in the feed were controlled at 20% by mass, which is the mean of the recommended 10–30%. The ring speed was set at the maximum of 4 r/min to prevent overloading of chromite onto the matrix. Pulsation was kept at 100 oscillations per minute to allow maximized cleaning and recovery of chromite interacting with the matrix.

Other parameters that could affect performance were not considered or controlled in this study. These parameters are particle size, particle shape, slurry viscosity, and the presence of magnetite, which will block the matrix due to its ferromagnetic property.

Experimental Method

Material from various sources was inspected for oversize and moisture, then screened at 1 mm and pan dried in an oven controlled at 40–60°C until dry and flowing. All samples were claimed to have P_{80} of less than 100 µm; this was not verified.

In cases where as-received samples were too large in volume the material was blended and then coned and quartered to remove around 50 kg of material for test work. Stickiness resulting from moisture prevented rotary splitting, and samples were deemed to be representative of the source.

A 20–30 kg portion (dry solids basis) of sample was weighed out and added to a predetermined volume of fresh potable water from Rand Water supply to make up a standard feed slurry of 20% solids by mass in the feed sump. The recycle and agitator were run at this time to ensure proper mixing. It was noted that cavitation of the feed pump, attributed to air in the feed slurry, resulted when the agitator was on while slurry was pumped to the header box; agitation was terminated moments before the feed valve was opened to initiate the feed to the header box. The slurry tank inside the separator was filled with fresh water. The machine was fed in a semi-batch operation with enough feed slurry to allow the run to reach a visually established pseudo-steady state some minutes into the run. It is expected that pseudo-steady state was achieved for at least ten minutes of the run, during which time product samples were collected. Recycle to the feed tank was maintained throughout a run to allow mixing of the solids throughout the slurry volume, but it is believed that some segregation of the heavy chrome solids nevertheless occurred across the height of the sump. Samples were collected in clean, plastic-lined drums by taking the full stream for the assumed steady-state duration of the run. There were volumes of holdup of material in the feed sump, feed lines, header box, return lines, and the WHIMS slurry tank that did not report through as products; these difficult-to-collect volumes were not always collected but care was taken to wash this material out in-between test runs. Feed samples were taken as grab samples from the recycle line return to the feed sump (with the agitator) running as reference. Wash water was adjusted to wash the concentrate from the matrix using a supply water valve, but the flow rate was not measured.

Product streams were left to settle until the water header at the top of the sample collection drum was clear, and then carefully decanted. The remainder of the drum was then dewatered in a vacuum suction filter pot through filter paper with sufficient backing to ensure drainage and prevent tears in the paper, thus avoiding any solids losses. No solids were seen to be lost in the filtrate. The vacuum-dried material was then transferred into stainless steel oven pans and dried at 40–60°C. Flakes of material that formed during drying (particularly noted in the nonmagnetic product pan, where higher slimes and silica were present) were manually crushed. The dry solids weights were recorded to allow subsequent mass balance calculations, and the samples handed back to the customers for analysis under agreements that results would be made available.

The nonmagnetics, middlings, and magnetic product weights were carefully recorded and the feed solids weight calculated as the sum of these weights. Mass pull was calculated using the weights recorded and recovery calculated using the product of the product stream weight and mineral grade.

The test runs were all confidential and therefore samples are only labelled as X and Y – where it was possible to conduct tests runs on 0.4, 0.7, 1.0, and 1.3 T; and A and B where test runs were conducted at 0.4 and 1.0 T only. All samples were UG2 material collected from unspecified locations of the tailings dams. Particle size distributions were not analysed as the sources confirmed that all material should have a P_{80} of less than 100 µm.

The Cr:Fe ratio was not tested as this was not a critical parameter for any of the clients.

Chemical analysis was done by potential clients' laboratories and the methods chosen were not within the author's control.

RESULTS AND DISCUSSION

Effect of Magnetic Intensity on Grade and Recovery of Chromite

Figure 7 shows the effect of magnetic background field intensity on chromite grade and recovery for sample X. It can be seen that chromite recovery increases from 50 to 70% as a result of increasing magnetic field intensity from 0.7 to 1.0 T. Conversely, recovery to middlings and tailings decreases. This result is expected, since more chromite particles will be attracted to the matrix elements and be transported out of the slurry bath to be recovered as magnetic concentrate. It can also be seen that the product grade decreases with increasing background intensity, as is expected: more nonmagnetic particles (assumed to be mostly silica) will be entrained with the magnetic concentrate. Furthermore, non-liberated particles will also be recovered at these higher intensities where the magnetic force acting on the interstitial paramagnetic mineral is now large enough to overcome the shear experienced on the surface of the total particle due to the slurry flow. Conversely, the chromite grade in the nonmagnetic tailings decreases as the magnetic field intensity increases, because more chromite is removed to the magnetic concentrate. Recoveries are calculated as the weight of mineral reporting to a stream divided by the total weight of that mineral in the feed stream. It is expected that recovery of chromite to the tailings stream will decrease as more of the chromite reports to the magnetic concentrate with increasing magnetic intensity. Variations in feed grade are noted between runs, possibly resulting from sample source variations.

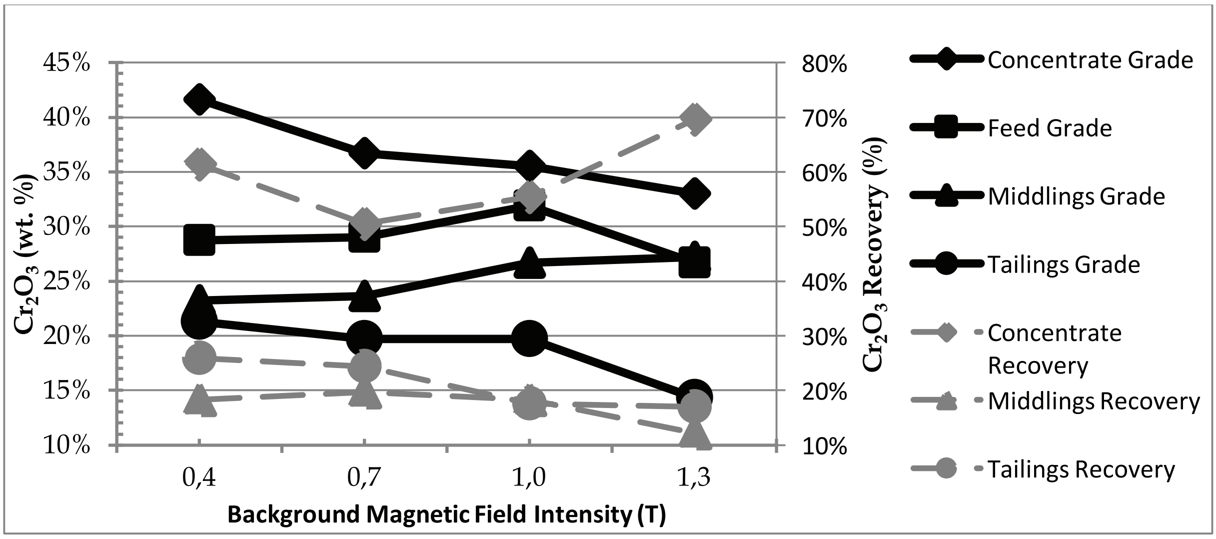

Figure 7. Cr_2O_3 grade and recovery versus background magnetic field intensity for sample X.

Figure 8 compares the chromite grades and recoveries of samples X and Y as a function of background magnetic field intensity. As expected, chromite recovery from sample X increases as the background intensity is increased from 0.7 through 1.3 T, while (surprisingly) that of sample Y decreases very slightly across this range. This could possibly be ascribed to a higher viscosity of the slurry resulting from sample Y, which counters the transport of the increasing amount of chromite particles that are pulled towards the matrix elements. This effect is possibly pronounced as more particles are excited by the magnetic field towards the matrix elements, where hindered settling effects could affect recovery adversely. The presence of flotation chemicals was indicated by the smell and by frothing of the slurry during the test run, and it is suspected that even though sample Y was from a tailings dam, it could have been recently arising material that still contained unreacted flotation chemicals.

It can also be seen that the concentrate grade for UG2 sample Y follows the same trend as for sample X. The upgrade ratio of sample Y (defined here as the ratio between the concentrate grade and the feed grade) is, however, substantially lower (1.39, 1.30, 1.24, and 1.24) for low magnetic field intensities, compared to that of sample X (1.45, 1.27, 1.11, 1.24) at background intensities of 0.4 through 1.3 T. It is proposed that the more viscous fluid discussed in the previous paragraph counters the transport of material to the matrix surface. Secondly, the viscosity around the matrix elements could also prevent displacement of nonmagnetic material from the surface of the element, resulting in more nonmagnetic material being entrapped and thus lowering the concentrate grade. However, as background magnetic field strength is increased it seems possible that the magnetic force is sufficient to overcome the proposed viscosity effects, and upgrade ratios seem to be in line with the results from sample X.

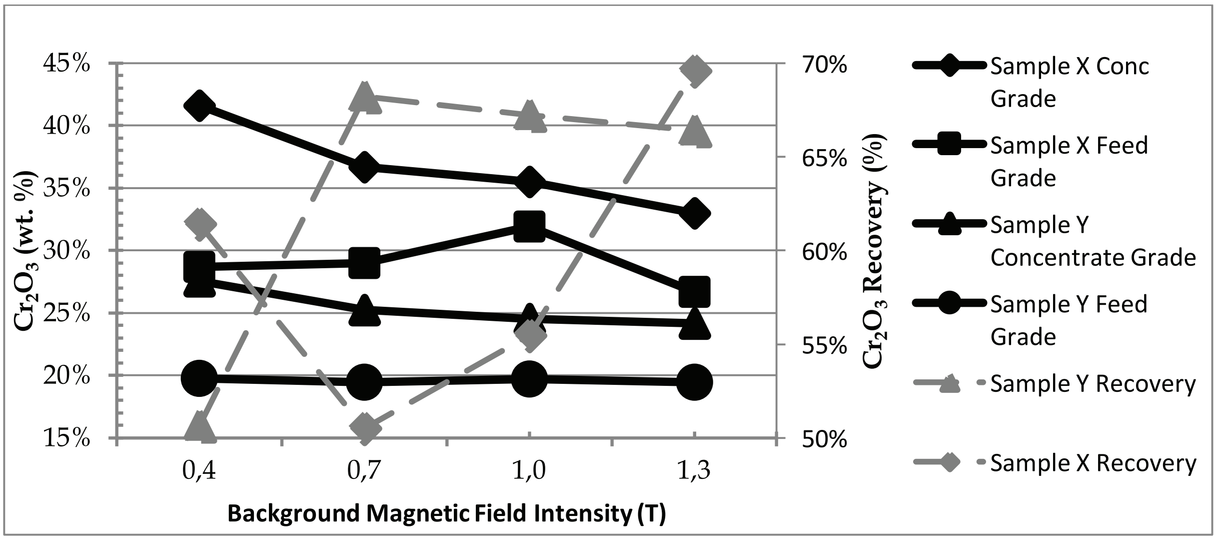

Figure 8. Cr_2O_3 grade and recovery versus background magnetic field intensity for sample X and sample Y.

Figure 9 shows the grade and recovery results for samples A and B, which were only subjected to background field intensities of 0.4 and 1.0 T. Even though the samples were from different sources their feed grades were similar. The concentrate grades produced were also very similar, at 31% and 27% at the two intensities. There is, however, a notable difference in recovery of almost 15% between the two samples. This result cannot be explained.

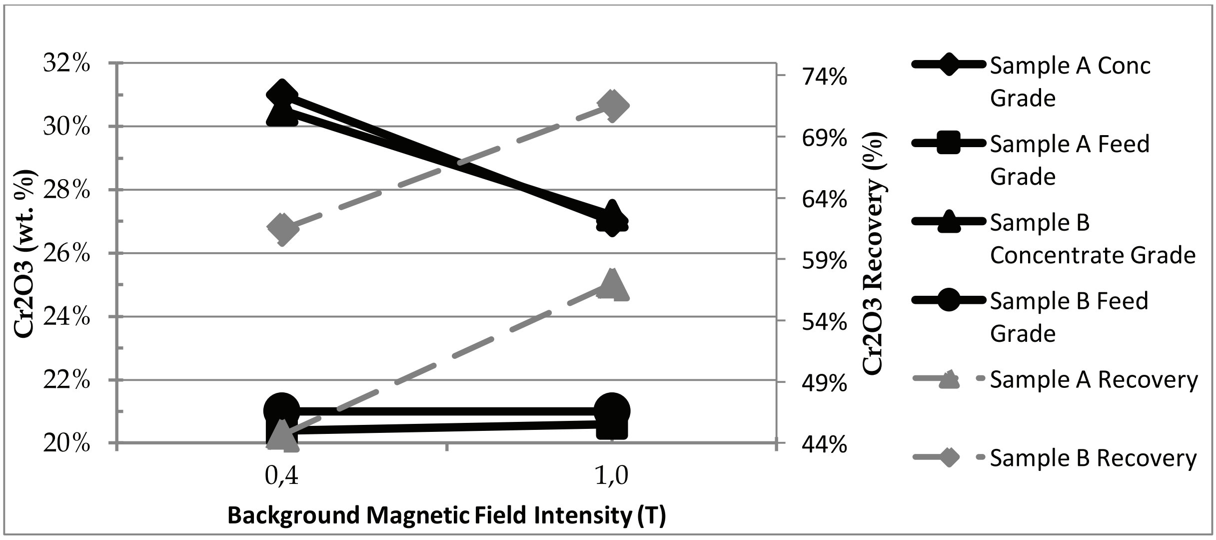

Figure 9. Cr_2O_3 grade and recovery versus background magnetic field intensity for sample A and sample B.

From the results discussed above, deeper investigation into the parameter(s) that affects the upgrade ratio is considered in Figure 10. As can be seen, the upgrade ratios for the various samples follow the same trend when plotted as a function of background magnetic field intensity. Even though the values are of the same order, there are differences that could be ascribed to the viscosity effects discussed before, particularly for sample Y results. The results indicate that the upgrade ratios at higher background field intensity are more consistent, proving that the increase in background magnetic field intensity can be sufficient to overcome these effects, but not without the sacrifice of increasing entrapped nonmagnetics or increased attraction of non-liberated material resulting in lower concentrate grades.

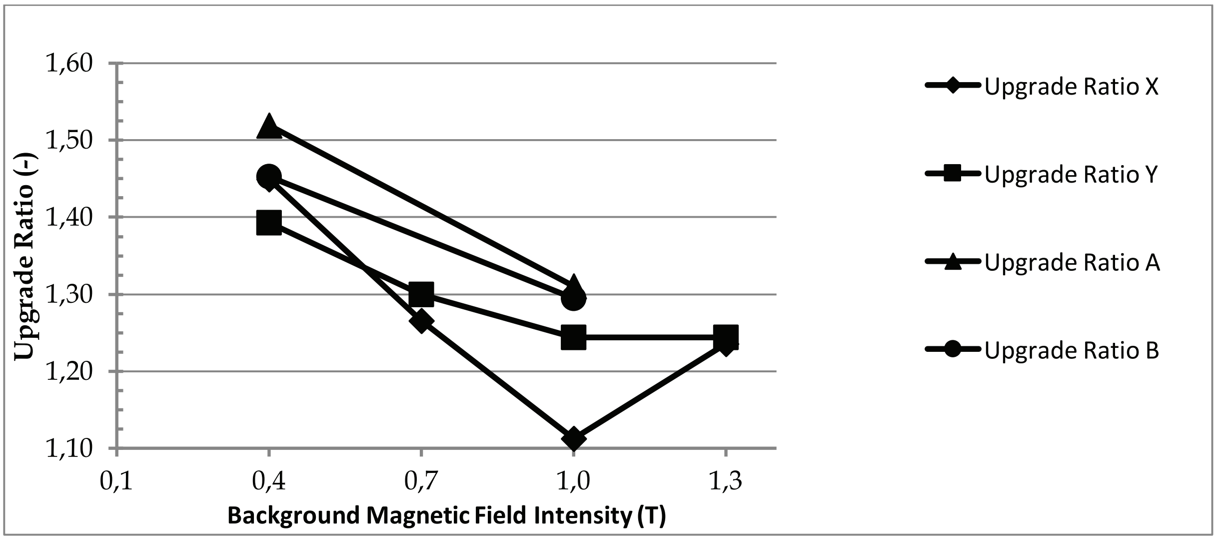

Figure 10. Upgrade ratio of chromite concentrate as a function of background field intensity.

A possible relationship between upgrade ratio and feed grade was investigated, but no correlation was evident (graph not shown here). This means that lower feed grades will be subjected to upgrade ratios that are (within the scope of this paper) only a function of magnetic field intensity.

Figure 11 shows the relationship between concentrate product grade and yield for all test samples. From the graph, an increase in magnetic field intensity generally resulted in an increased yield and a decreased concentrate product grade owing to the factors discussed above. The grade *versus* yield result for sample Y is the lowest, again emphasising the suspected viscosity effects. The grades versus yield values for different samples are significantly different and the response to magnetic separation must be tested to confirm the response for a specific sample. Further investigation into other parameters that affect the separation is recommended.

These discussions above prove that grade and recovery results are very predictable except at lower intensities, where site-specific higher viscosity effects could adversely influence grade and recovery. Inevitably more stages of WHIMS will be required to upgrade material to the required saleable grade of 42%. The number of stages will be determined by the recovery that is required; high overall recovery will require machines to be run at 0.4 T, whereas recoveries are typically reported here over a broad range of 15–32%. Site-specific work on fresh arising and older material, where no active flotation chemicals are present, is strongly recommended. This work should also identify the presence of magnetite in the material to determine the size of the scalping wet drum magnetic separator that must be installed prior to WHIMS.

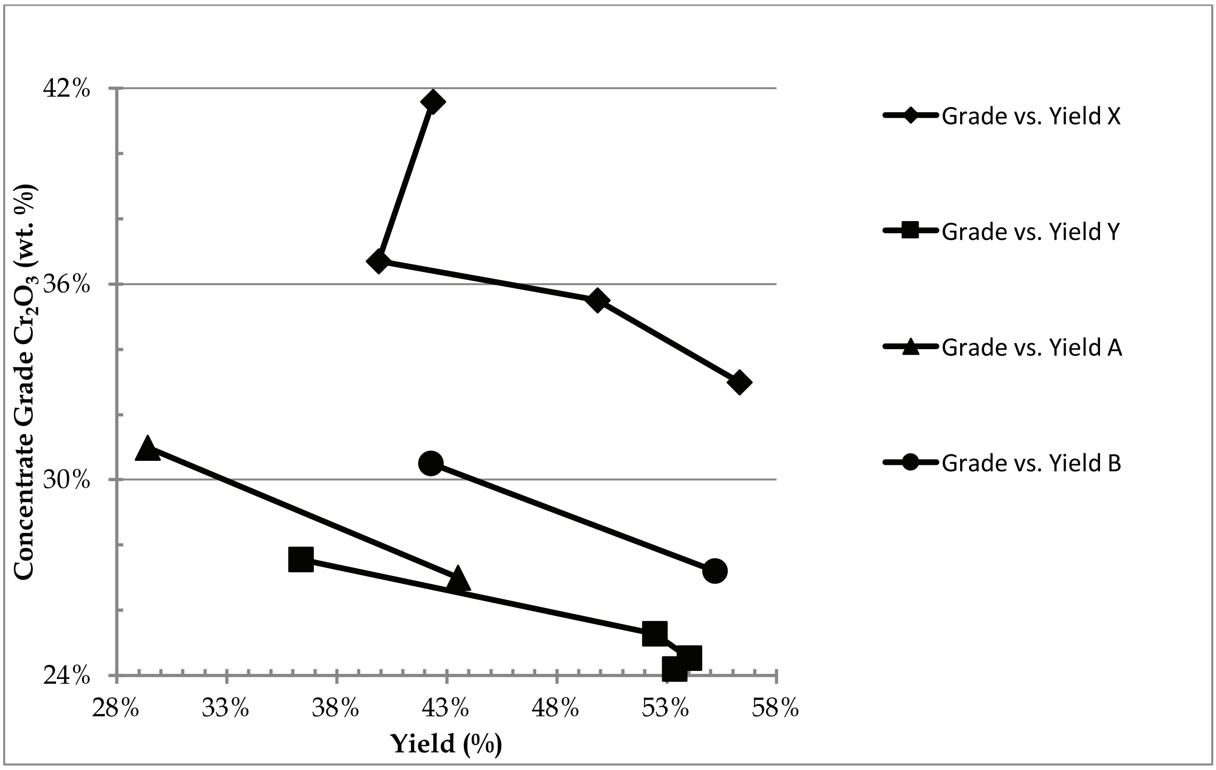

Figure 11. Concentrate grade versus yield for Cr_2O_3 for all four test samples.

Effect of Magnetic Intensity on Grade and Recovery of PGMs

Figure 10 shows the reverse upgrade effect of chromite removal to the magnetic concentrate on the PGM concentration in the middlings and tailings streams of samples X and Y. Reasonable reverse upgrades are possible, and recoveries to the combined middlings and tailings streams are more than 60%, with recoveries as high as 80% achieved. PGM grades were as high as 6.5 ppm, which could indicate that re-floating of these streams would be economically viable, as the threshold is believed to be around 4 ppm. Results are, however, limited and more test work runs are recommended.

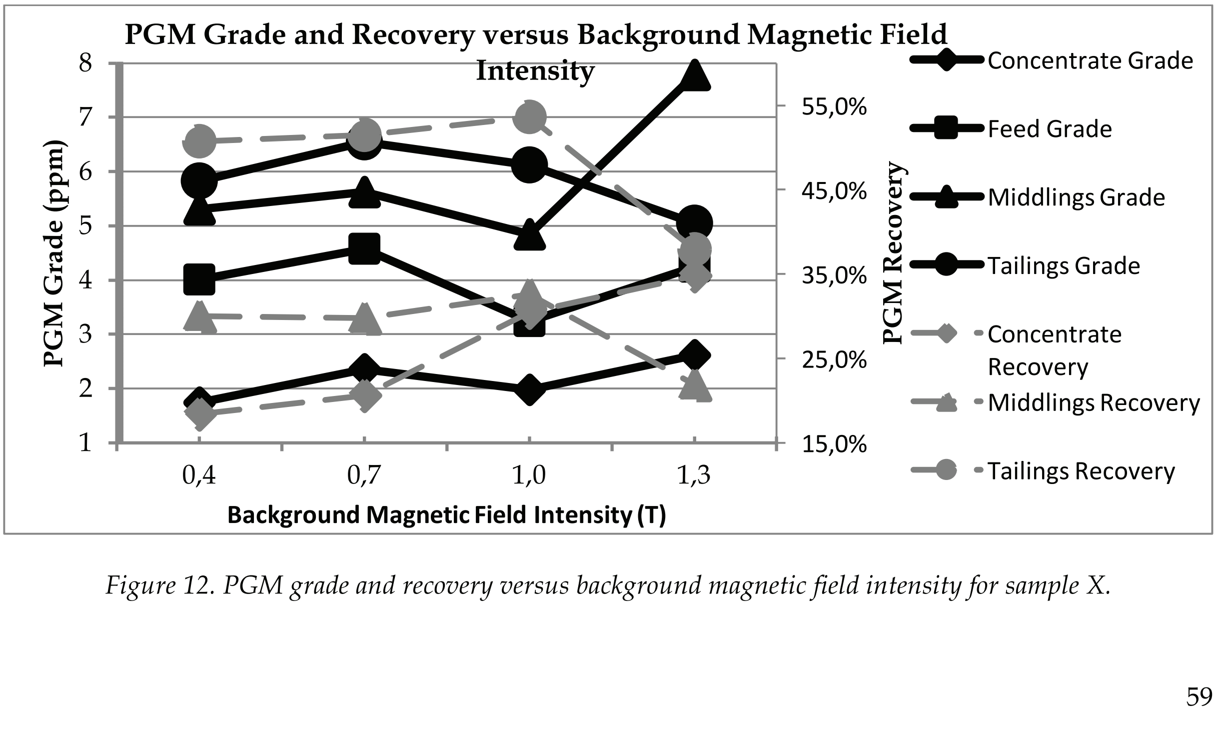

Figure 12. PGM grade and recovery versus background magnetic field intensity for sample X.

CONCLUSIONS AND RECOMMENDATIONS

Effect of Magnetic Intensity on Grade and Recovery of Chromite

Very fine chromite from gravity separation circuit tailings can be upgraded using a vertical ring WHIMS. Chromite recoveries to the magnetic concentrate range between 44–62% at 0.4 T and 55–72% at 1.3 T. Yields varied from 27–42% at 0.4 T and generally decreased with increased magnetic intensity to 1.3 T, where yields were between 24–33%. Recoveries and yield are strongly dependent on background magnetic intensity, but more importantly seems to be site-specific.

Upgrades of 6–14% were achieved at 0.4 T and 4–6% at 1.3 T. Upgrade ratio analysis proved that upgrade is a function of magnetic intensity, but not of chromite feed grade.

The broad ranges of grade and recovery values are suspected to be the result of different viscosities, attributed to the possible presence of unreacted flotation chemicals or ultra-fine material. Differences in mineralogy and liberation of chromite from different source materials could also account for the broad range of grades, recoveries, and yields and should be further investigated.

Further results indicated that at higher background magnetic intensities the proposed viscosity effects are diminished as larger magnetic forces act on particles and overcome these counteracting forces. However, as the background intensity increases, grade decreases and recovery and yield increase, which means inevitably more stages of WHIMS will be required to upgrade material to the required saleable grade of 42% Cr_2O_3.

Site-specific work on fresh arisings and older material, where no active flotation chemicals are present, is strongly recommended. This work should also aim to identify the presence of magnetite in the material to determine the size of the scalping wet drum magnetic separator that must be installed prior to WHIMS.

The reverse upgrade of PGMs in the vertical WHIMS tailings stream through chromite removal to the magnetic concentrate stream seems feasible, with tailings grades of up to 6.5 ppm achieved at a PGM recovery of 50%. It is believed that this stream could be floated economically to recover additional PGM material. The advantage of processing existing tailings streams lies in the cost savings, since mining, conveying to surface, and milling have already been done.

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Willem Pieter Slabbert

Applications and Process Manager
Multotec Process Equipment (Pty) Ltd

Willem is a Master's degree graduate that started his working career in water treatment and industrial filtration before joining Multotec Process Equipment (Pty) Ltd in February 2012. His experience and responsibilities includes magnetic separation, where he serves as Multotec's Product Specialist, centrifuges and filtration as well as wet and dry Sampling, where he serves as Applications and Process Manager.