Optimization of magnetite recovery circuits in a navigation coal-washing plant challenged with scaling due to gypsum formation

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Abstract. In 2023, the Navigation coal-washing plant recorded the highest magnetite consumption per tonne within the Thungela group. With declining commodity prices, cost competitiveness remains critical for sustainability. In 2024, focus shifted to reducing magnetite consumption, improving plant efficiency, and optimising processing costs. Key interventions included optimising primary magnetic separators, improving spray-water pressure, and selecting appropriate screening media. These were supported by regular pressure-jetting, improved piping configurations, automatic flushing sprays, and maintaining consistent head-tank levels. As a result, magnetic separator efficiency increased from 95% to 99%, and magnetite adhesion losses dropped by 4.85 kg per screen tonne. Despite these gains, magnetite consumption remained 1.05 kg per feed-to-plant tonne above the 1.20 kg target. A key challenge is pipe scaling caused by gypsum formation, driven by acid mine drainage and excessive limestone dosing in water treatment. Reducing limestone use and introducing a scaling inhibitor are expected to curb sulphate-related reactions and improve recovery. Additionally, re-using water from the top of the active slimes compartment—without neutralisation—will further reduce pipe scaling. These efforts aim to enhance water quality and eliminate magnetite under-recovery, supporting long-term operational efficiency.

1 Introduction

During 2023, Navigation Plant's magnetite consumption per tonne proved to be the highest within the Thungela group. With declining commodity prices, cost-competitive practises are critical to improve competitiveness. The cost lever within the business is essential to contributing meaningfully to cash generation within Thungela's asset portfolio. In 2024, the reduction in magnetite consumption, which was achieved by improving the in-circuit magnetite recovery, attracted renewed focus to improve the cost per tonne profile of the coal-washing plant.

A strategy was developed to isolate and improve on deficient operational practices within the magnetite recovery circuit. The recovery of magnetite in the coal-washing plant is impacted by the water quality produced from the limestone treatment plants upstream of the coal-handling and processing plant (CHPP). Historically, the Navigation complex feed water

has always been acidic as it accumulates in groundwater compartments, where it is impacted by coal discards. This means there is a need to treat this water with limestone for the purposes of pH neutralisation. The scaling phenomenon is then observed through the formation of excess calcium ions in solution, which then react with the sulphates in the water throughout the circuit and cause the build-up of gypsum in screen spray-water piping and on medium recovery screen decks, magnetic separator drums, medium reception tanks and manifolds. The effects of gypsum on these areas of the magnetite recovery circuit make the efficient recovery of magnetite extremely challenging.

2 Theory

Numerous operational practises need to be standardised and managed in the coal handling and processing plant to enable the efficient recovery of magnetite.

2.1 Navigation plant magnetite recovery circuit

Navigation Plant consists of two modules, EF and GH. For the sake of brevity, one module (EF) is discussed. All equipment numbering remains the same, except for 'E' corresponding to 'G' and 'F' corresponding to 'H' with the respective modules. In total there are four magnetite recovery circuits within the plant. Fig. ***1*** is a flow diagram that depicts Navigation Plant's 'E' magnetite recovery circuit.

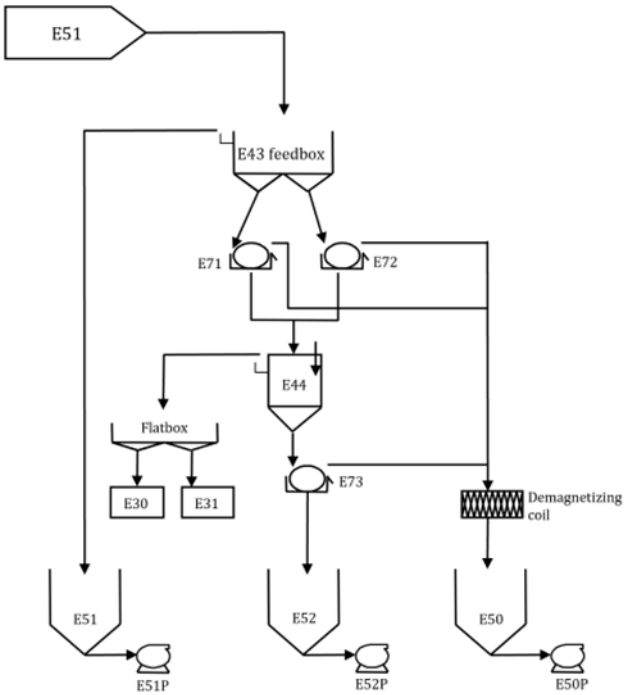


Fig. 1. Schematic representation of Navigation Plant's 'E' magnetite recovery circuit.

Table 1 describes the equipment used to recover magnetite at Navigation Plant.

Table 1. Navigation Plant's 'E' magnetite recovery circuit.

Equipment number	Description
E71, E72	Primary magnetic separators
E73	Secondary magnetic separator
E44	Settling cone
E30	Drewboy product screen
E31	Drewboy discard screen
E50	Correct medium tank
E51	Dilute medium tank
E52	Effluent tank
E50P, E51P, E52P	Transfer pumps

Dilute medium is pumped to the primary magnetic separators. The over-dense pulp from the primary magnetic separators is demagnetised and transferred to the correct medium tank. The underflow from the primary magnetic separators reports to the settling cone and thereafter to the secondary magnetic separators. The over-dense from the secondary magnetic separator is demagnetised and transferred to the correct medium tank. The underflow from the secondary magnetic separator reports to the effluent tank. The dilute medium from the overflow of the settling cone reports to the Drewboy product and discard screens as a pre-wash stage.

In addition to the magnetite recovery circuit, adequate spillage reclamation and magnetite spillage handling techniques are in place to recover medium back into the circuit by means of sump pumps. This is supported by adequate protection against the ingress of oversized material and foreign objects.

2.2 Water quality and reticulation

Water from the opencast mine, pollution control dams, and toe-seepage from the mineral residue facility is managed through an extensive pumping network consisting of both diesel and electrical pumps. This mine-affected water is pumped off-site to the Emalahleni Water Reclamation Plant (EWRP) to dewater the site and on exception - re-used internally to support the continuous open-cast mining activities, upholding compliance to pollution control dam freeboard requirements, and ensuring a consistent supply of process water for the dense medium separation (DMS) plant.

Due to the acidic nature of the feed water, the Navigation Complex has relied primarily on internal liming plants to neutralize the pH of the acidic feeds treated to produce process water. This water is used for coal washing in the coal handling and processing (DMS) plant. Limestone is introduced at the Primary Liming and toe-seep treatment plants to drive the required neutralization reactions. The unintended consequence of this treatment is that the water accumulates a high concentration of sulphate ions which drive the precipitation of gypsum when limestone is dosed. Equation 1 illustrates the precipitation reaction responsible for gypsum formation [1].

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO4 + 2H_2O \quad (1)$$

The internal water recovery of the plant is sustained through the recovery of supernatant water from the overflow of the thickeners. The thickener underflow is pumped onto a slurry compartment at the mineral residue facility, where suspended solids are beached out and the clarified supernatant pool of water is then decanted via a penstock for reuse in the DMS plant.

The water quality does, however, deteriorate significantly as it is reclaimed from the top of the penstock, where it varies between pH 5.8 and 6.5, to the bottom outlet of the return water pipeline, where it varies between pH 2.6 and 3.8. This deterioration is the reason the water needs to be treated, resulting in the scaling of the water pipelines in the CHPP. This, in turn, negatively impacts on the recovery of magnetite in all the washing circuits.

In March 2024, the integrity and condition of the penstock return water pipe was investigated using a remote-controlled CCTV camera. This revealed that displaced concrete joints along the horizontal section of the penstock pipeline are allowing seepage in the discards of the MRF to enter the penstock pipeline and contaminate the good-quality return water. This compromises the quality of the water, making it less suitable for reuse within the DMS plant. Consequently, additional limestone is then necessary to neutralise the impacted water which, in turn, results in the accelerated precipitation of gypsum within the system.

2.3 Magnetic separators

Magnetic separators can be configured in different ways to optimize magnetite recovery in a DMS plant.

In a co-current configuration, the drum of the magnetic separator rotates in the same direction as the slurry flow as it is introduced to the drum. This design allows the drum to transport magnetics toward the over-dense discharge side, resulting in a longer residence time for magnetic particles within the separator feed tank. Conversely, in a counter-current configuration, the drum rotates in the opposite direction of the slurry flow. This results in a shorter residence time, which enhances the recovery of magnetics from the slurry [2].

Navigation Plant is equipped with eight primary magnetic separators and four secondary magnetic separators, all featuring three-meter drums and operating in a counter-current configuration to maximize magnetite recovery efficiency.

2.4 Drain and rinse screens

Drain-and-rinse screening is a widely used industry technique designed to recover and recycle the medium within the DMS circuit. In this process, the medium is first drained from the material and returned to the system (correct medium). The material is then rinsed with water to recover any remaining medium adhering to the particles, forming a dilute medium. Finally, excess water is allowed to drain towards the discharge end of the screen, forming the effluent stream.

2.4.1 Screen spray-water

Sustained screen spray-water pressure is crucial to overcome the adhesion of the magnetite to the product coal and discards. However, the formation of gypsum within pipelines restricts water flow to the drain-and-rinse screens, resulting in high magnetite losses from the screens and under-recovery of the medium.

Fig. ***2*** illustrates the typical reduction in flow area available for water to drive the recovery of magnetite. The pipeline diameter that supports the required flow due to gypsum formation is then reduced and the pipeline pressure rises due to the reduced flow in the pipeline. Fig. ***3*** highlights the inadequate spray-water supply to the drain-and-rinse screens caused by gypsum build-up in the delivery pipelines. Additionally, spray nozzle blockages are a direct consequence of the gypsum build-up in the pipelines. For optimal magnetite recovery, a continuous curtain of spray water – at 70 kPa pressure - should be maintained across the entire width of the screen deck to ensure efficient rinsing to sustain magnetite recovery.

Fig. 2. Gypsum formation within pipelines.

Fig. 3. Compromised spray-water pressure on DMS plant drain and rinse screens.

2.4.2 Screen drainage

An adequate open area for drainage in the selected screening media is a crucial factor in ensuring effective magnetite recovery. The formation of gypsum on screen decks leads to the blinding of screen panel apertures, which significantly reduces drainage efficiency and impacts magnetite recovery. As a result, regardless of the effectiveness of spray-water, magnetite under-recovery will still occur.

At Navigation Plant, a maintenance routine is in place to stay in step with the blinding of screening media through high-pressure cleaning of screen decks. This is to mitigate gypsum build-up. It is, however, time-consuming and labour-intensive, and only supports the plant running from one maintenance day to the next.

2.4.3 Material residence time

To optimise magnetite recovery on the drain-and-rinse screens, material residence time must be optimal. Counter-weight settings, that affect screen amplitude and vibration frequency, must be considered when optimising material residence time on a drain and rinse screen. A reduction in screen amplitude or vibration frequency will result in a decrease in the forward momentum of the particles on the screen deck resulting in an increased residence time. By increasing the screen amplitude and vibration frequency, an inverse effect in particle momentum will be observed.

Material bed depth on the screen deck is a crucial factor that must be considered. A reduction in screen amplitude or vibration frequency will result in a decrease in material bed depth, thereby increasing magnetite recovery, however, screening efficiency will be negatively impacted. By increasing the screen amplitude and vibration frequency, an inverse effect in material bed depth will be observed [3].

A balance must be obtained between screen amplitude and vibration frequency to obtain the optimal material bed depth for maximum magnetite recovery and screening efficiency.

3 Methodology

3.1 Magnetic separator optimisation

Initial magsep efficiencies were quantified and several demonstrated efficiencies below 95%. A first principles approach was taken, and the following physicals of the magnetic separators were optimised:

- Drum height
- Operating level
- Magnet height above discharge lip
- Squeeze gap

To conduct the analysis, representative samples were taken from the feed to the magnetic separator, the over-dense concentrate, and the effluent before and after adjustment of the above physical parameters. Approximately fifteen one-litre increments were collected from the feed and fifteen from the over-dense medium. These increments were spaced out over a duration of approximately 30 minutes while the magnetic separator operated under normal conditions. The collected feed samples were combined into a composite sample and the same technique used for the over-dense samples. Similarly, for the effluent, a representative composite sample was collected.

Subsequently, the samples were sealed, clearly labelled, and sent to the laboratory for the following analyses:

1. The mass of each sample was measured.
2. Solids in each sample were filtered and dried, and their mass was documented.
3. Representative sub-samples were extracted from the solids in each sample. In the case of the effluent, all the solids were required, and a sample splitter was employed.
4. Using a Magna-Chute, the percentage of magnetic and non-magnetic components in each sample was determined.
5. The efficiency of the magnetic separator on a mass basis was calculated.

3.2 Drain and rinse screen optimisation

The maintenance strategy for managing pipeline scaling through high-pressure jetting to descale was revised to increase the frequency from six-monthly to quarterly. Additionally, modifications to the spray-water feed lines were implemented to minimize the number of pipeline bends, to mitigate pressure drops that contribute to gypsum buildup. To further enhance sustained spray-water pressure, the header tank minimum operating levels were increased from 50% to 75%.

Spray-water manifolds, that were previously declared redundant, were recommissioned to each drain and rinse screen to ensure additional recovery of the magnetite. Additionally static screen panel apertures on the preparatory desliming screens were revised from 0.8 mm to 1 mm slotted apertures. The newly installed panels provide an increased open area,

improving desliming efficiency and grit removal. To further optimize screening conditions, the screening media was upgraded from polyurethane to rubber, creating a more flexible and live screening surface. Additionally, a row of panel apertures beneath the spray manifolds on each cyclone circuit drain and rinse screen was increased from 0.63 mm to 1 mm to enhance open area and mitigate the risk of blinding due to gypsum buildup.

In addition, to sustain spray-water efficacy, self-flushing spray nozzles were installed on all the drain and rinse screens. The self-flushing spray nozzle comprises of the body of the spray with a pneumatically controlled piston in the centre of the spray. The piston controls the volume and pressure of the spray-water. Constant air pressure keeps the piston in the closed position, allowing wash water to spray in a controlled manner onto the screen deck. A reverse pulse of air allows the piston to extend to the fully opened position, allowing any gypsum build-up to be flushed out. These gypsum particles would block standard spray nozzles and would have to be removed via a time-consuming, manual process. Changing the air flow to the initial mode reverts the piston to its original wash position. These nozzles actively mitigate for blockages by self-cleaning on a set-frequency to ensure consistent spray-water distribution for improved magnetite recovery.

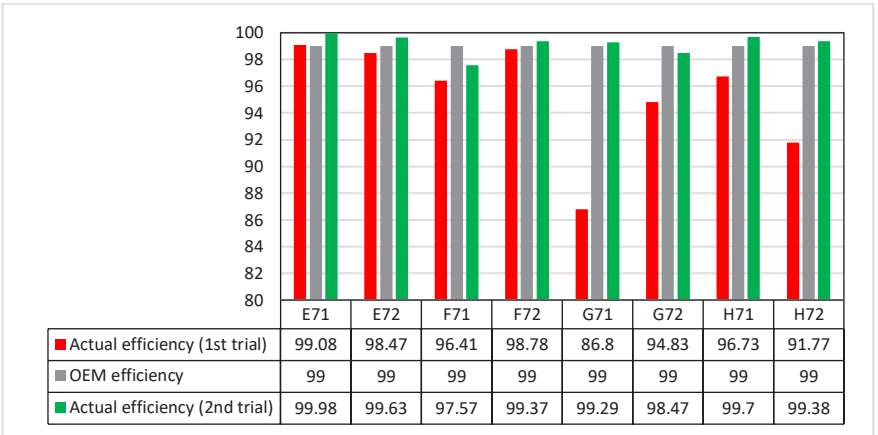
Some interventions were done to quantify magnetite adhesion losses before and after the above changes and modifications were rolled out:

1. Representative screen samples were collected.
2. The samples were washed with clean water to recover magnetite that adhered to the particle surface.
3. The wash-water from the material – containing the collected magnetite was passed over the Magna-Chute to recover magnetic material.
4. The magnetic material was dried and weighed.
5. The clean sample that was collected from the screen was allowed to dry.
6. Adhesion losses were calculated.

4 Results

4.1 Magnetic separator efficiencies

Fig. *4* shows the primary magnetic separator efficiencies before and after physical adjustments. E71 – H72 on the figure refer to the primary magnetic separator equipment numbering at Navigation Plant.



	E71	E72	F71	F72	G71	G72	H71	H72
Actual efficiency (1st trial)	99.08	98.47	96.41	98.78	86.8	94.83	96.73	91.77
OEM efficiency	99	99	99	99	99	99	99	99
Actual efficiency (2nd trial)	99.98	99.63	97.57	99.37	99.29	98.47	99.7	99.38

Fig. 4. Navigation Plant primary magnetic separator efficiencies.

Following the physical adjustments made to the primary magnetic separators, an increase in recovery efficiency was observed. The average magnetic separator efficiency increased from 95% to 99%, matching the stated OEM efficiency.

4.2 Drain and rinse screen adhesion losses

Table 2. Magnetite adhesion losses per drain and rinse screen (kg t^{-1}). shows the magnetite adhesion losses per drain and rinse screen before and after discussed changes were rolled out. F35 – H38 refer to cyclone drain and rinse screen equipment numbering at Navigation Plant.

Table 2. Magnetite adhesion losses per drain and rinse screen (kg t^{-1}).

	F35	F36	F37	F38	H35	H36	H37	H38	Average
Before	3.49	3.99	3.51	12.14	6.21	19.47	9.45	3.63	7.74
After	3.26	3.24	3.34	9.25	0.73	0.30	1.14	1.75	2.89

A significant overall improvement was observed following the implementation of the changes to the drain and rinse screen sprays, feed-water pipelines, screening media and steady-head tank operating level. An average decrease of 4.85 kg per screen tonne of magnetite loss due to adhesion was quantified.

During sample collection, it was observed that the self-flushing spray nozzles were still blocking due to gypsum accumulation. Thus, the plant is unable to run on the required spray-water pressure from maintenance day to maintenance day. Following this observation, larger self-flushing sprays, with a bigger opening, were tested. The following physical changes were made to the spray nozzles to improve spray cone size and throughput volume:

- The length of the spray nozzle was increased from 140 mm to 235 mm.
- The outer diameter of the spray nozzle was increased from 47 mm to 74 mm.
- The flush opening was increased from 20 mm to 35 mm.
- The spray-water feed opening was increased from 20 mm to 40 mm.

The test yielded positive results of a decrease in adhesion losses from 1.69 kg per screen tonne to 0.86 kg per screen tonne, demonstrating the effectiveness thereof. Fig. ***5*** depicts the enhanced screen spray-water following the modifications.

Fig. 5. Screen spray-water following modifications to the automatic flushing sprays.

5 Conclusion and recommendations

Following the physical adjustments made to optimise the primary magnetic separators and the changes implemented on the drain and rinse screens with respect to spray-water pressure, screening media selection, pipeline high-pressuring routines, pipeline modifications,

automatic flushing sprays, and steady-head tank operating level, a noticeable increase has been observed in the magnetic separator efficiency and a noticeable decrease has been observed in the magnetic separator efficiency and in-circuit magnetite recovery.

The improvement in the magnetic separator efficiencies to within OEM specification was achieved, and to some extent improvements in the adhesion losses on the drain and rinse screens can be observed with the above interventions. It was observed that the improvement in magnetite recovery was far more significant on the H-screens when compared to the F-screens. Theoretically, both F- and H-circuit should have yielded similar results. This presents the opportunity to re-baseline magnetite adhesion losses and reconduct the tests. Furthermore, the physical drain and rinse screen set-up can be fine-tuned to optimise material residence time for enhanced magnetite recovery whilst maintaining optimal screening efficiency. However, further improvement would need to come from improving the scalability of the process water which is still an inherent challenge in the plant.

The effects of gypsum build-up on the magnetite recovery can threaten the sustainability of the coal washing plant due to magnetite being such a significant cost driver. Despite the efforts made to reduce magnetite consumption, Navigation Plant was still 1.05 kg per feed-to-plant tonne above the target consumption of 1.20 kg per feed-to-plant tonne.

Further work in the cost reduction initiative at Navigation plant for magnetite will require an improvement in the scalability of the process water used. More recently, the introduction of a scaling inhibitor promises to introduce another lever that will assist to manage the reaction of the sulphates from the water treatment plants downstream, this will form part of the next phase of test work.

Future work to improve the feed water quality will also involve investigating the water and infrastructure management practices at the tailings dam penstock. It was observed that the water is contaminated at the penstock horizontal pipe, hence the ability to either repair this pipe or extract better quality water at top of the penstock and feed it directly to the coal-washing plant will be explored. This will reduce the amount of limestone required to neutralise and also the amount of sulphates present which will improve the scalability and reduce gypsum formation. Furthermore, additional work in the water treatment plants in terms of optimal residence time in the aeration tanks and clarifiers to ensure that the precipitation reaction does not go to completion upstream of the CHPP is crucial. These initiatives are currently underway to sustain the progress that has been made in enhancing Navigation Plant's magnetite recovery.

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