Stabilisation of the Nickel Sulphide Concentrate Volumetric Flow Rate and Implementation of Mass Pull Control Strategy at Nkomati Mine

Ike Madingoana,[1,2] Antoine F. Mulaba-Bafubiandi[1] and Stephan van Zyl[2]

[1] Mineral Processing and Technology Research Centre, University of Johannesburg, South Africa
[2] Nkomati Mine, Machadodorp, South Africa

Corresponding author: ike.madingoana@gmail.com

The study presents a control strategy implemented at the Nkomati nickel mine flotation plant for process stabilization and improvement. The control strategy involves flotation concentrate volumetric flow rate stabilization and the flotation cell mass pull control. The flotation concentrate volumetric flow rate is operated at a fixed set point. The initial control strategy involved varying the flow rate to maintain the concentrate tank level thereby reducing pump cavitation. The flotation cells mass pull control comprises air rate manipulation into the cells with the exception of the recleaners. The air rate into cells is automated to adjust based on the concentrate tank level variation. The control strategy was implemented on the roughers, cleaners and the recleaner circuit. The recleaner cells air flow rate is adjusted based on the MgO content in the concentrate. The stabilization of the flotation concentrate volumetric flow rate and the mass pull by aerate automation will increase the scope of optimization for further process improvement. The immediate benefit of the control strategy implementation was plant stability. Disturbance to the flotation cells downstream was minimized due to stable flow rate, and the air addition manipulation ensured that the concentrate tank levels are maintained, minimizing pump cavitation.

INTRODUCTION

Froth flotation is a challenging process because it is influenced by a large number of factors, including the flotation feed characteristics. One of the ore types mined at Nkomati nickel mine is the main mineralized zone (MMZ). The MMZ ore is hosted in the Uikomst complex, a Ni-Cu-PGE-Cr-mineralized, layered basic to ultra-basic intrusion which hosts commercially viable magmatic base-metal sulphides (De Waal et al., 2001). The MMZ ore is a heterogeneous sulphide mineral resource with a varying sulphide mode of occurrence and texture. The beneficiation of the complex sulphide ore is challenging due to the presence of impurities in the ore. The impurities report to the flotation final concentrate and penalties are levied if the impurities are beyond the contractual limits.

The decline in the nickel price compelled stringent control of the froth flotation process to maximize production without compromising the product quality and the overall plant recovery. The outputs from the plant can be maximized by rapid response to process deviations from the key performance indicators. The study proposes stabilization of the flotation concentrate volumetric flow and automation of the air rate to the flotation cells to control the mass pull of the cells.

Volumetric flow rate is one of the critical process parameters needed to understand and control the flotation process (O'Keefe et al., 2012). The initially applied control strategy around the flotation concentrate tanks was to manipulate the concentrate flow rate to avoid running the concentrate tanks empty. Running the concentrate tank low creates gas pockets at the suction end leading to pump cavitation. The flow-rate control strategy was implemented to prolong the life of the pumps. Cavitation can give rise to erosion damage, noise, vibration and hydraulic performance deterioration by periodic inception, growth, depletion of vapor bubbles (Thai et al., 2010). However, volumetric flow rate variability is one of the flotation cells level disturbance variables. Flotation level control becomes challenging when the feed to the cells is variable, even when an advanced level controller is in place. Reducing the volumetric flow rate variability was essential in establishing and maintaining a stable flotation process plant.

The flotation concentrate tank level control can be achieved by controlling the concentrate mass pull. The flotation concentrate mass pull can be controlled by various parameters, such as the depressant dosage, flotation frother, collector, cell level and air addition rate into the cell. The manipulated variable that was elected for the proposed control strategy was the air addition rate. Singh et al. (2003) observed that response on the concentrate sump level was quicker when the air rate into the cells was changed. The other known flotation variables are considered if the air addition does not succeed in curbing the disturbance experienced at the flotation circuit.

An on-line analyzer was installed to aid the flotation final product quality control. The gangue component of final concentrate product is represented by the magnesium oxide content of the assay results and the real-time grade data. Magnesium oxide (MgO) is a pseudorepresentative of all the magnesium-bearing oxide gangue minerals. Grade control from the mineral concentration step can greatly minimize production delays on the down-stream processes. The air addition rate to the final flotation stage is controlled based on the grade data.

PROCESS DESCIPTION

The ore for the plant is sourced from the underground and open-pit mining operations. The blending ratio is around 80% open pit and 20% underground. The open-pit ore is gyratory-crushed and conveyed to the MMZ plant feed stockpile. The underground ore is jaw-crushed prior to conveyance to the MMZ plant stockpile. The MMZ plant employs run-of-mine (ROM) milling with a fully autogenous (FAG) mill as the first milling stage. The FAG mill product is subjected to screening where the screen undersize reports to the cyclone. The screen oversize (pebbles) reports to the cone crusher. The crushed product recirculates to the FAG mill feed. The cyclone underflow reports the ball mill. The ball mill product combines with the FAG mill product and reports to the cyclone. Figure 1 shows a MMZ flotation plant process overview.

The cyclone overflow gravitates to the conditioner and is subjected to the following flotation steps:

- The rougher feed is split into two streams that gravitate to the first and second banks that consist of 5×130 m^3 cells per bank. The combined rougher concentrate is pumped to the cleaners. The combined rougher tailings gravitate to two banks of 3×100 m^3 scavengers. The scavenger concentrate is combined with the rougher concentrate and pumped to the cleaners. The scavenger tails gravitate to the tailings thickener for water recovery prior to tailings disposal.
- The rougher + scavenger concentrate is pumped to 5×50 m^3 cleaner cells and the tailings from the cleaners are pumped back to the roughers. The cleaner concentrate is pumped to the re-cleaners.
- The recleaner (3×30 m^3) tails gravitate back to the cleaners. The concentrate from the final cleaners is collected and pumped to the concentrate thickener.

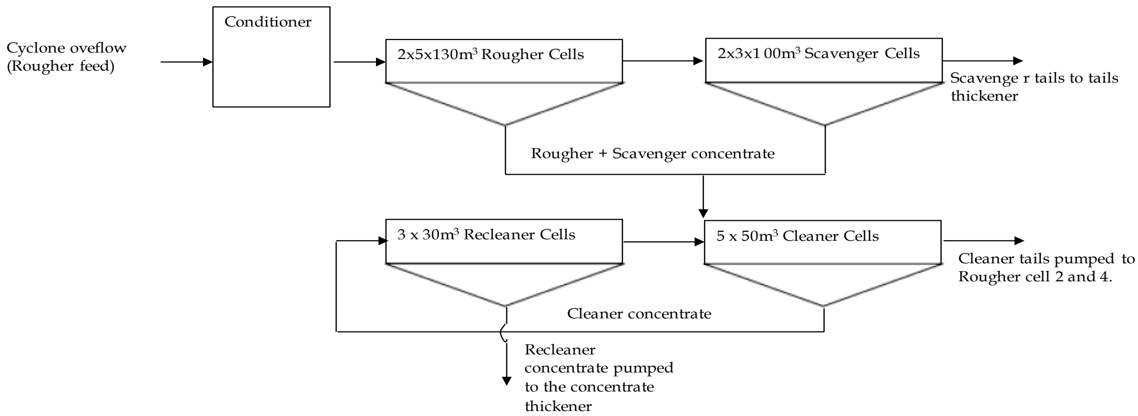

Figure 1. The MMZ plant flotation circuit overview.

CONTROL STRATEGY

The control strategy is divided into two stages. The first stage entails controlling the flow rate around a fixed set point. The second step of the control strategy entails employing air rate to control the mass pull of the cell.

Rougher Concentrate Tank Level Control Loop

The rougher concentrate is laundered to the rougher concentrate tank with the function of absorbing surge and to maintain a stable flow to the cleaners. The tank is equipped with a level indicator and an agitator to de-aerate the concentrate before it is pumped to the next flotation circuit. The tank is also equipped with spray bars to assist froth break down. The tank level was deliberately allowed to fluctuate within certain limits: upon exceeding those limits, an output signal is activated and step changes in the VSD (variable speed drive) pump speed implemented.

The difference between the control before and the control after is that the flow rate will be operated at a fixed set point. The flow rate will be operated at 450 m^3/h for the rougher concentrate. The cleaner concentrate flow rate set point is manually adjusted based on the circuit performance; the set point is adjusted between 200 and 250 m^3/h. The recleaner air inputs are controlled based on the on-line analyzer grade data available in real time. The major focus on the real-time grade data is the MgO content. The neutral operating zone is a range of between 4 and 6.5 % MgO in the recleaner concentrate stream.

Mass Pull Control

Once the flow of the rougher concentrate and the cleaners was fixed to operate around a non flexible set point, the next optimization step was controlling the mass pull of the cell by air addition rate manipulation based on the concentrate tank level. Flotation cell mass pull control will assist in minimizing the concentrate tanks running empty due to concentrate pumps operating independently of the conditions of the individual banks concentrate tank levels. .

The air addition into the cells is triggered when the concentrate tank levels for the roughers and the cleaner concentrate tank level exits the neutral zone (dead band). When the tank level exits the neutral zone, a signal is relayed to the PLC (programmable logic controller) to initiate adjustments based on action rules that are incorporated into the control strategy. The tank level is monitored in closed loop until the level returns to the neutral zone. The control strategy around the recleaners is different, as has already been highlighted: action will be triggered by the MgO content of the recleaner concentrate stream. The following tables detail the control action.

RESULTS AND DISCUSSION

The results are split into two sections: first, the operating efficiency of control strategy is assessed and, thereafter, the metallurgical benefit of the control strategy is discussed.

Control Strategy Assessment

The control strategy on the roughers was the first to be implemented after the mass pull control strategy was suggested by Gipronickel consultants. After successful implementation on the roughers, the project was rolled down to the cleaners and the recleaners. The control strategy on the cleaners and recleaners was implemented on 22 February 2015, as indicated in Tables I to III.

The scavenger circuit is not included in the control strategy. The scavenger circuit has been reconfigured to function as extended rougher cells. The exclusion of the scavenger circuit is a result of back pressure when the tails exit the circuit, thereby leading to abrupt level control. Test work is currently underway to determine the best possible solution to the problem experienced around the scavenger circuit.

Table I. Recleaner circuit air control strategy.

	Description	Limits		
Set point	Level (%)	50		
Controlled variable	MgO (%)	4–6.5		
Manipulated variable	Air flow rate	Operated within an operating window		
Action table (pump action)				
Condition	MgO level (%)	Action (air control (m^3/min)		
High level (HL)	> 6.4	–0.03	–0.02	–0.01
Dead band	4–6.5	Neutral zone – no action		
Low level (LL)	< 4	0.03	0.02	0.01

Table II. Rougher circuit control strategy.

	Description	Limits	
Set point	Level (%)	60	
Controlled variable	MgO (%)	0–1005	
Manipulated variable	Air flow rate	Operated within an operating window	
Action table (pump action)			
Condition	Tank level (%)	Action (air control (m^3/min)	
		Ro. 1 + 2 + 3 + 4	Ro 5 + 6 + 7 + 8 = 9 + 10
Critically high level (CHL)	77.5–100	–0.08	–0.04
Very high level (VHL)	70–77.5	–0.04	–0.02
High level (HL)	60–70	–0.02	–0.01
Dead band	50–60	Neutral zone – no action	
Low level (LL)	40–50	0.02	0.01
Very low level (VLL)	30–40	0.04	0.02
Critically low level (CLL)	0–30	0.08	0.04

Rougher Flow Rate Control

Figure 2 summarizes the results obtained before and after the implementation of the stringent flow control and mass pull control optimization. Two random days were selected to best depict the two operating conditions. 144 data sets, collected every 10 minutes, were analyzed per component (rougher concentrate flow and rougher concentrate tank level) before and after implementation of the control strategy. A tighter flow control is displayed on Figure 3 where the data analyzed show a standard deviation of 4. The target flow control was at 450 m^3/h, as has already been highlighted, whereas the flow was allowed to fluctuate between 300 and 400 m^3/h. The standard deviation on the flowrate before the old control strategy implementation was 18, with an average flowrate of 373 m^3/h. The initial flowrate control was dependent on the tank level, which was effectively maintained by the rougher cells mass pull. If the rougher mass pull drops, the pump speed slows down in attempt to maintain the tank level. A synchronized oscillation between the tank level and the concentrate tank level can be seen with the initial control employed. The concentrate pump speed continued to drop until a manual intervention, such as air adjustment, depressant change or cell level change, is instituted to improve the mass pull of the roughers. The current control strategy shows a detachment between the rougher concentrate tank level and the concentrate pump flowrate. Figure 3 shows stringent flow control according to set point, regardless of the condition of the tank level. On two occasions, the tank overflows at a relatively constant flowrate.

Table III. Cleaner circuit air control strategy.

	Description	Limits		
Set point	Level (%)	60		
Controlled variable	Level (%)	0–100		
Manipulated variable	Air flow rate	Operated within an operating window		
Action table (pump action)				
Condition	Tank level (%)	Action (air control (m^3/min)		
Critically high level (CHL)	77.5–100	–0.08	–0.06	–0.04
Very high level (VHL)	70–77.5	–0.04	–0.025	–0.02
High level (HL)	60–70	–0.02	–0.015	–0.01
Dead band	50–60	Neutral zone – no action		
Low level (LL)	40–50	0.02	0.02	0.01
Very low level (VLL)	30–40	0.04	0.025	0.02
Critically low level (CLL)	0–30	0.08	0.06	0.04

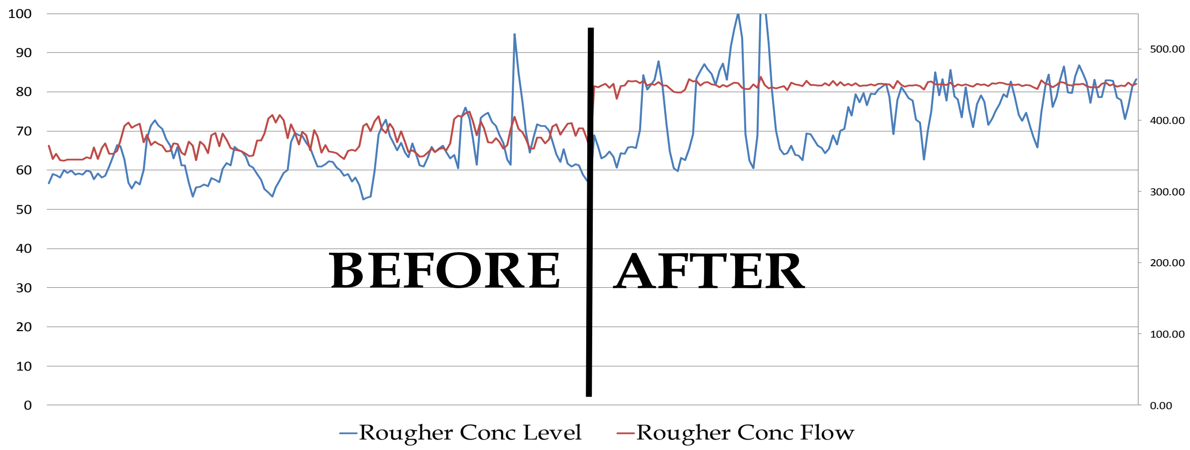

Figure 2. Rougher concentrate flow profile before and after.

The implementation of the flow and mass pull control was monitored using heat maps. Heat maps are graphical plots of the historical (SCADA) data. Figures 3 and 4 show heat maps for the rougher concentrate flow profile before and after implementing the flow control strategy. The different flow conditions are depicted by colour gradients, where the lowest values are on the light green tile and the highest values are on the red. The data for prior implementation of the control strategy were collected from 01/03/2013 to 30/06/2014. The data used to generate the heat maps were collected from 01/03/2014 to 30/06/2014 to assess the flow profile after the control strategy was implemented.

The immediate benefit of the flowrate control can be seen by examining the cleaner cells dart valve operation. When the flowrate to the cleaners fluctuates, the dart valve operation is not stable. The dart valve operation is also assisted by implementation of FloatStar® flotation level optimization. Figure 5 shows that the standard deviation on the cleaner feed level operation drops significantly when the flowrate to the cleaners is controlled stringently, compared with when the flowrate was allowed to oscillate to control the rougher concentrate. The cleaner dart valve operation relaxes significantly when the flow rate to the cleaners is operated around a fixed set point. The cleaner dart valve operation is also affected by the recirculation load from the recleaners. The cleaner mass pull is affected by the concentrate quality, which is greatly influenced by the type of ore that is being processed at the time. When the feed grade to the plant reduces and the recleaner concentrate quality is affected, mass pull on the recleaners drops and thus increases the total flow (rougher concentrate feed + recleaner tails flow) to the cleaners, which also affects the operation of the dart valves.

MMZ.ARR_104_FIT_101.F_1

CLEANER CONC FEED m3/hr

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
A					513.99	507.23	517.74			
B			463.46	495.29	519.05	498.25	522.91	527.35	636.44	
C			474.85	471.70	505.49	526.32	581.88	592.53	747.72	
D		402.97	396.46	439.06	470.46	510.25	575.19	623.45	563.81	504.98
E	334.76	373.39	402.00	416.63	452.36	493.89	554.45	610.40	632.50	498.77
F	327.50	338.13	348.20	385.98	433.83	481.82	538.18	562.54	529.36	479.58
G		300.81	347.85	365.13	471.33	451.85	492.66	529.35	500.39	
H			296.06	339.06	382.28	412.26	428.45	462.79	559.23	
I				329.88	339.72	388.93	429.95	483.38	503.49	
J					346.53	360.35	372.92	418.76		

Figure 3. Rougher concentrate flow profile before control strategy implementation.

	1	2	3	4	5	6	7	8	9	10
A		450.5	458.4	451.6	442.5					
B	455.9	453	461.6	454	464.5	450.4	463.1			
C	468.6	460.8	467.2	458.5	446.3	442.9	458.3			
D	462	461	464.7	453.7	457.6	445.8	446.9	438.4	443.3	452.3
E	467.1	460.7	467.3	463.1	452.9	448.8	444.4	448.1	442.1	434.9
F	459.3	465.8	463.3	460.5	458.9	457.4	452.1	449.5	449.6	443.4
G	448.4	462.5	468	460	459.2	455.8	449.1	441.4	447.2	443.6
H	460.2	472	472.3	466	459.6	454.7	448.1	460	454.6	416.5
I	468.8	480.6	475.1	468.9	454.9	458.7	452.1			
J	464.1	462.9	469.5	471.1						

Figure 4. Rougher concentrate flow profile after control strategy implementation.

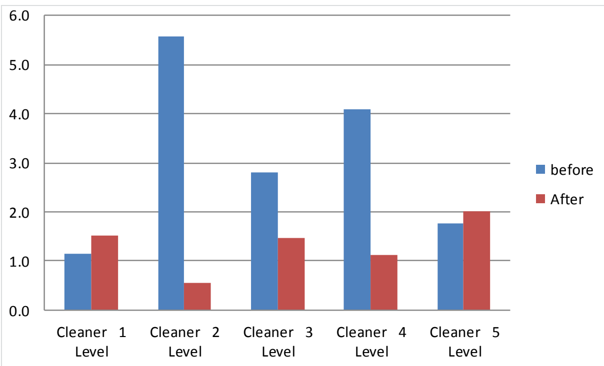

Figure 5. Cleaner level standard deviation before and after flow rate.

The cleaner dart valve operation has relaxed significantly when the flow rate to the cleaners is operated around a fixed set point. The cleaner dart valve operation is also affected by the recirculation load from the recleaners. The cleaners mass pull is affected by the concentrate quality and which is greatly influenced by the type of ore that is being processed at the time. When the feed grade to the plant reduces and the recleaner concentrate quality is affected, mass pull on the recleaners will be dropped thus increasing the total flow (rougher concentrate feed + recleaner tails flow) to the cleaners, which will also affected the operation of the dart valves.

Rougher Cells Air Rate Control

Figure 6 shows a general inverse relationship between the air flowrate addition into the rougher concentrate cells and the rougher concentrate tank level. The air addition rate into the cell reacts to the tank level percentage or rise rate. When the tank level rises, the air addition rate into the cell drops, as has already been mentioned, to help mantain the tank rougher concentrate tank level. The addition rate into the rougher cells increases when the tank level drops.

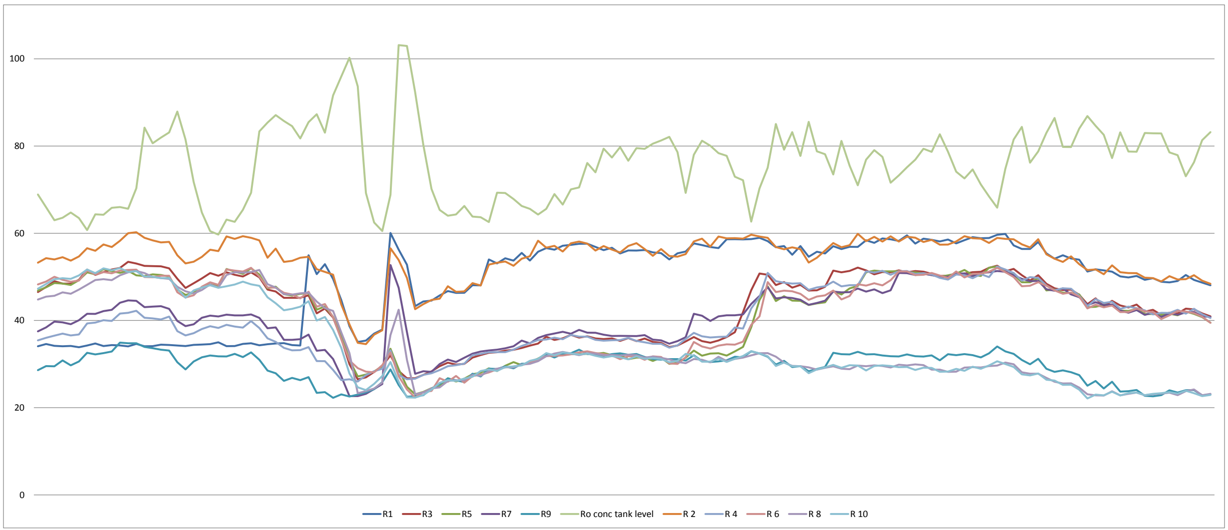

Figure 6. Rougher cells air flow rate tracking vs rougher concentrate level.

Cleaners and Recleaners

The air addition control on the cleaners and recleaner does not operate as aggressively as that of the roughers (Figure 7). The stable control on the cleaners and recleaners is attributed to the constant feed flow rate from the roughers. The rougher circuit is subjected to multiple variables that warrant the aggressive response from the air addition rate control strategy. The variables affecting the roughers include the mill feed rate, the mill feed material characteristic and rougher feed density. The disturbances are curbed in the rougher circuit; hence an aggressive air addition rate control can be seen on the roughers, thereby making the control on the cleaners and recleaners relatively easier. The mass pull control operation on the cleaners has been seamless since implementation.

Metallurgical Benefit of the Control Strategy

Since the complete control strategy around the circuit was fully implemented on 22 February 2015, insufficient data was analyzed to get a full assessment of the impact that the control strategy has on the overall plant recovery and recleaner concentrate grade control. The data analyzed are from 1 January to 26 March 2015.

These data indicate that there was no immediate benefit of the mass pull control on the recovery (Figure 8). The head grade treated at the plant varied significantly, which had a direct impact on the plant recovery. Figure 9 shows a crude plot of the float feed grade and the overall plant recovery. The head grade variation makes it challenging to fully evaluate the impact of the mass pull control on the overall plant recovery. The major benefit immediately observed post-implementation of the mass pull control is plant stability. The average head grade before mass pull control and flow stabilization implementation was 0.37 % for 50 data points. The average weighted recovery was 73.08 %at a nickel concentrate grade of 9.09 % and Fe/MgO ratio of 6.32. The average head grade after implementing the control strategy was 0.4 % for 32 counts of data. The average weighted recovery was 74.4 % which is 1.32 % points higher than prior to the control strategy implementation, but the average head grade was also higher.

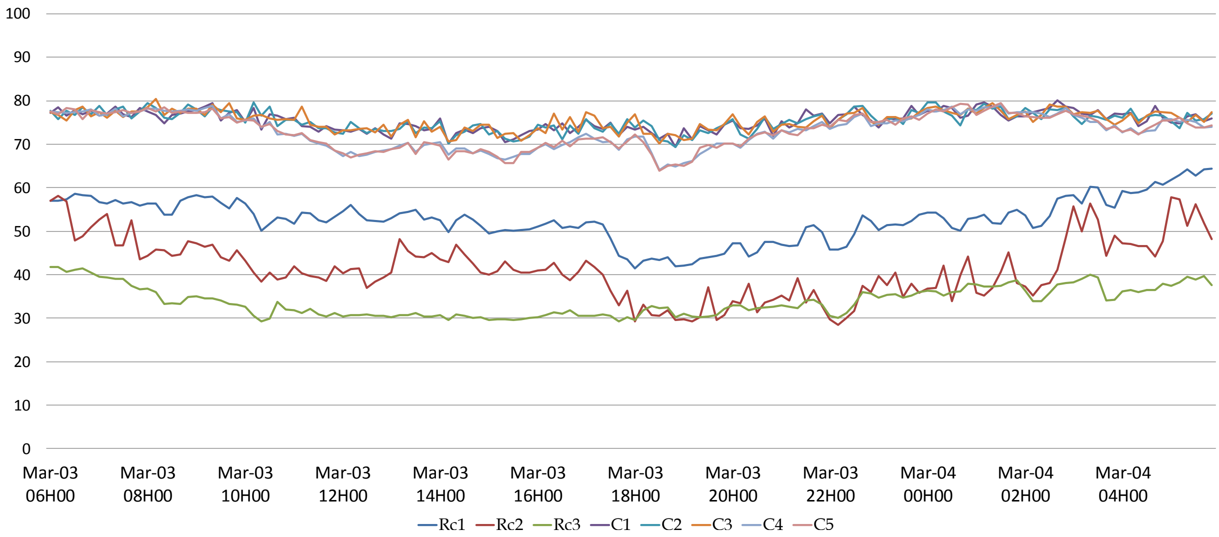

Figure 7. Cleaner and recleaner air tracking (m/s).

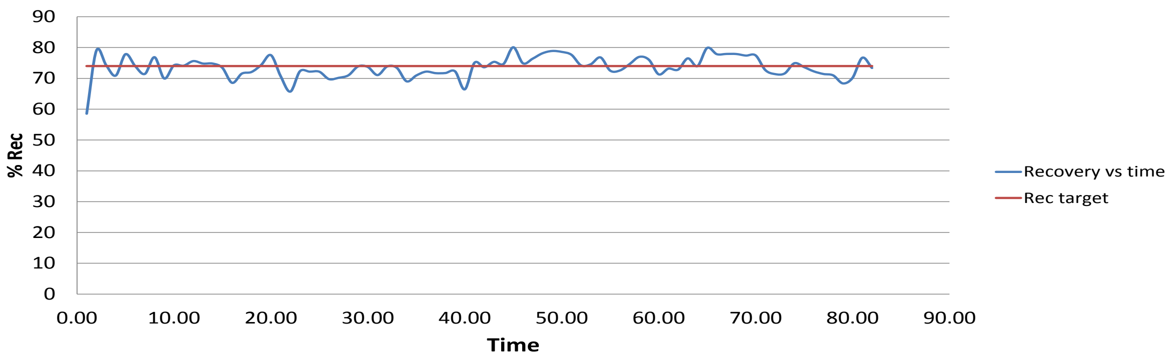

Figure 8. The recovery vs. time.

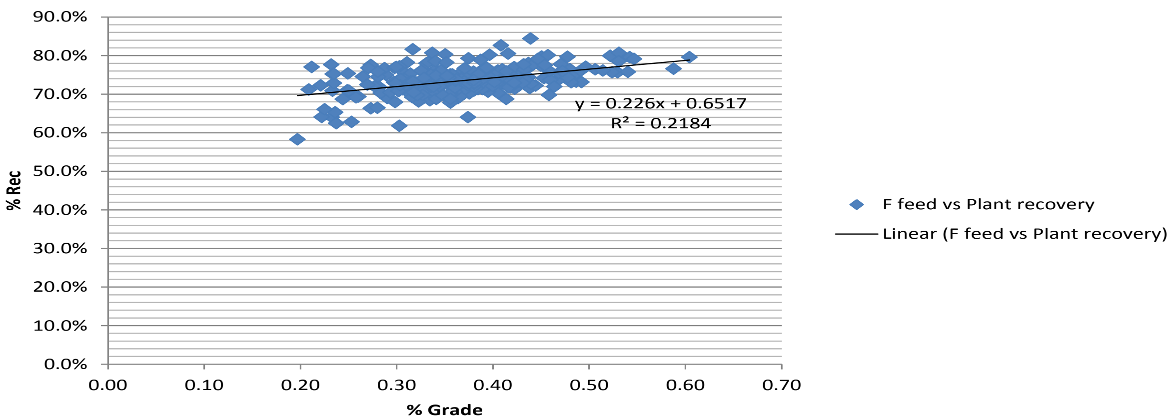

Figure 9. Plant recovery vs. head grade.

Before implementing the control strategy, the MgO grade had been oscillating vigorously (Figure 10). The benefit of control based on MgO in the recleaner concentrate stream is that the grade of the Fe/MgO in this stream has not moved out of the target operating range since implementing the control strategy. The amount of naturally floatable gangue minerals is therefore minimized. The Fe/MgO ratio grade prior to implementing the control strategy was some points below the minimum ratio requirements. However, controlling the ratio to within the higher limit is still challenging, with ratios of some points being above 12. The Fe/MgO ratio gives an indication of the mass pull of the recleaners. If the Fe/MgO ratio is too high, this implies that the recleaner mass pull needs to be improved. Improving the recleaner mass pull will help reduce the recirculation load which will, in turn, increase the overall plant recovery. The Fe/MgO oscillation is also an indication that the prediction accuracy of the installed online analyzer needs to be reviewed. A summary of the laboratory composite results compared with those of the on-line analyzer MgO grade data is presented as Figure 11.

The function of the on-line analyzer is to make grade data available in real time. The requirement from the on-line analyzer is to predict grade data that are close to the composite assay grade results. A comparison of the laboratory assay results and the on-line analyzer grade data showed a correlation of 37%, which implies that the prediction accuracy needs improvement to aid the control strategy. The standard deviation on the data analyzed was 1.10 for the laboratory composite assay and 0.67 for the online analyzer data.

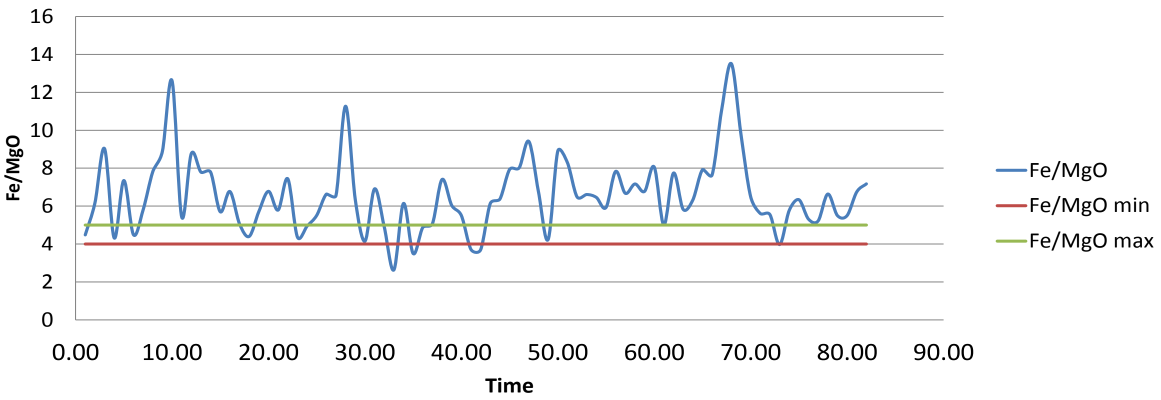

Figure 10. Fe/MgO ratio.

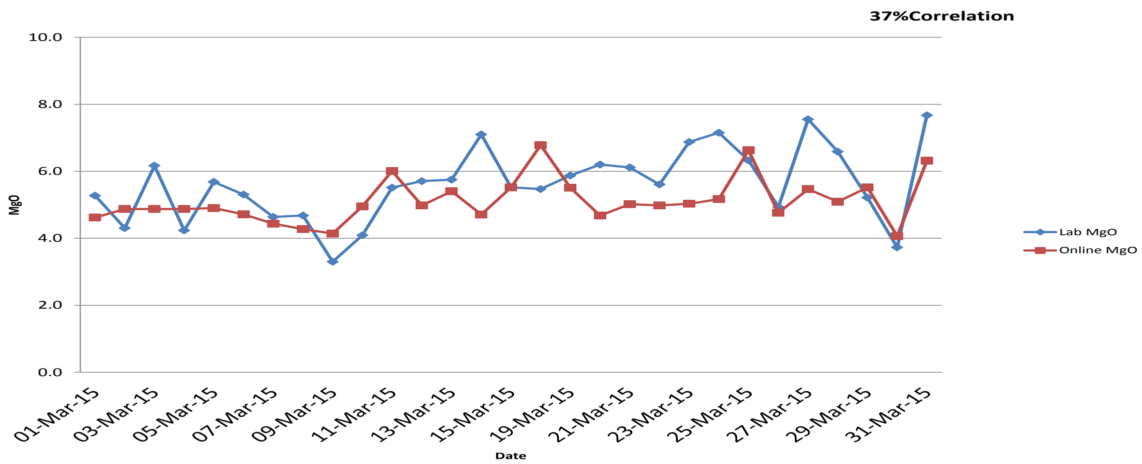

Figure 11. Comparison of MgO analyses from the laboratory and from the on-line analyzer.

CONCLUSION

Plant stability has improved since implementing the control strategy around the flotation circuit. The overall plant recovery has not shown a significant improvement because this is affected by the feed grade. The feed grade analyzed during and after control implementation varied between 0.2 and 0.6% Ni, thereby making assessing the impact of the control strategy on the overall plant recovery challenging. An on–off strategy will be employed and the data analysis needs to continue. The challenge, however, remains in improving the mass pull on the recleaners by better sensitivity to the high Fe/MgO ratio level by the on-line analyzer. A concerted effort in calibrating the on-line analyzer is deemed necessary.

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