Iron Ore 2015 Conference

Paper Number: 108

Optimisation of Wash Water on an Iron Ore Spiral to Improve Grade

C.M. Ramotsabi[1], W Erasmus[2] and F Bornman[3]

1. R&D Engineer - Multotec Process Equipment, 28 Forge Road, Spartan, South Africa. Email: christinar@multotec.com

2. General Manager - Gravity Concentration Division, Multotec Process Equipment, 28 Forge Road, Spartan, South Africa. Email: wynande@multotec.com

3. Technology Manager - Multotec Process Equipment, 28 Forge Road, Spartan, South Africa. Email: faanb@multotec.com

ABSTRACT

Spiral concentrators are gravity based separation devices used for the preparation of coal, iron and heavy mineral ores (Wills, 1992). Gravity concentration remains the main separation method for fine iron ore and is used extensively for treating many minerals. Gravity concentration methods separate minerals of different specific gravity by their relative movement in response to gravity and one or more other forces, the latter often being the resistance to motion offered by a viscous fluid, such as water or air (Wills, 2006).

The main operating variables for a spiral concentrator are the feed rate, the slurry concentration, the wash water addition and the position of the splitters used to separate the tailings, middlings and concentrate streams (Sadeghi, Bazin & Renaud, 2014). Wash water is an important control variable used to wash away entrapped light minerals from the concentrate stream (Burt, 1984; Bouchard, 2001). Sadeghi et al. concluded the spiral operation to be sensitive to the wash water flow addition and resultant economic trade-off. Increasing the wash water flow rate increases the concentrate grade at the expense of the iron recovery.

The paper addresses the effects of dripping wash water onto the concentrate stream of a spiral processing fine iron ore. The dripping wash water system offers a low flow alternative and could possibly provide a good balance between grade and recovery of valuable minerals without using excessive water. The Multotec SC20HC/7 WW spiral was used for the experimental test work. The spiral was tested at varying solids concentrations; the wash water rate and the splitter positions were kept constant.

The use of wash water at 30%, 35% and 40% solid concentration improved the Fe grade in the concentrate (MO A+B) by about 1.5%, 6%, and 8% respectively. The additional SiO_2 rejected by the wash water is approximately 3%, 9%, and 11% at 30%, 35% and 40% solid concentration respectively. Addition of wash water is shown to have minimum effect on grade at 30% solid concentration, Fe upgrades obtained with and without wash water were found to be similar. Notable upgrades were observed at 35 and 40% solid concentration with wash water. The results obtained suggest that the additional SiO_2 rejection by wash waters increases with an increase in solid concentration. This suggests that the benefit of using the drip system is notable at higher solid concentration. It is believed that at lower solid concentration SiO_2 particles are reasonable free to move around and are possibly less entrapped than at high solid concentration.

The Fe grade/recovery and solid concentration relationship with wash water showed a non-linear correlation. The Fe grade increases with an increase in solid concentration up to somewhat optimum point and then drops as solid concentration increases further. The recovery of Fe on the other hand follows a converse relationship with solid concentration, the recovery decreases from 30% to 35% solid concentration and then increases again at 40% solid concentration. The increase in recovery at higher solid concentration could possibly be explained by the fact that the mass yield to concentrate also increases with solid concentration. Since recovery is a function of both grade and mass yield, the higher recovery at 40% solid concentration is likely due to the high mass yield obtainable at 40% solid concentration.

The drip system could therefore possibly offer a safe guarding against grade and solid concentration variations without using excessive water, and possibly ensure that a product within specification is maintained.

INTRODUCTION

Spiral concentrators are low energy consuming devices that separate minerals mainly on the basis of density. Spirals are widely used in mineral processing as a method for pre-concentration and have proven to be efficient and cost effective. Spirals have a wide application, they are used in iron ore processing, coal, gold, chromites, mineral sands, glass sands, and in soil cleaning.

Separation on a spiral is achieved through a combination of forces that act on particles as they move down the trough of the spiral. The main forces known to act on the particle on a spiral are the gravitational forces, centrifugal force, hydrodynamic drag, lift and friction forces (Kapur & Meloy, 1998). Apart from the forces acting on a spiral, the properties of the slurry flowing on a spiral including, solids concentration, feed rate and wash water also plays an important role in the separation on the spiral.

Control of solids concentration on a spiral is very important as it influences separation and recovery on a spiral. Recovery on a spiral has been shown to increase with an increase in solids concentration up to a point where it is optimum and then drops at relatively high solids concentrations (Richards & Palmer, 1997).

When separation is in progress on the spiral, the heavy particles migrate toward the inner region of the trough, the concentration of these dense particles becomes high and as a result the ease of flow of material becomes reduced. This bed of particles, in a spiral without wash water, can prevent further separation of the particles, resulting in silicates being trapped. Wash water is an important control variable used to wash away entrapped light minerals from the concentrate stream (Burt, 1984; Bouchard, 2001). The use of wash water on spirals can be used to restore the fluidity of the material to avoid beaching and to wash away the trapped silicates (Holland - Batt, 1995). The wash water can also wash away the valuable minerals to the tailing section; Sadeghi et al (2014) showed that an increase in wash water rate enhances grade but simultaneously increases the loss of valuable minerals to the tailings section. Positioning of the wash water is also important; it plays a role in reducing the misplacement of the valuable minerals to the tailing stream. Positioning the wash water nozzles to the middling section of the spiral trough has been shown to enhance recovery of heavy minerals while washing away the gangue (Ramotsabi, Erasmus & Bornman, 2015; Reddy, Krüger, Ramotsabi & Lincoln, 2010).

The aim of this study is to investigate the effect of the dripping wash water system on grade and recovery on iron ore material. The Multotec SC20HC/7 WW spiral was used for the experimental test work. The spiral was tested at varying solids concentrations; the wash water rate and the splitter positions were kept constant. Optimization of these variables is expected to provide optimum conditions for a good compromise between grade and recovery.

EXPERIMENTAL

Material

The sample was obtained from the Kumba Iron Ore plant, near the town of Kathu in the Northern Cape Province of South Africa. The -1mm hematite sample was a low grade with an average head grade of 36% Fe.

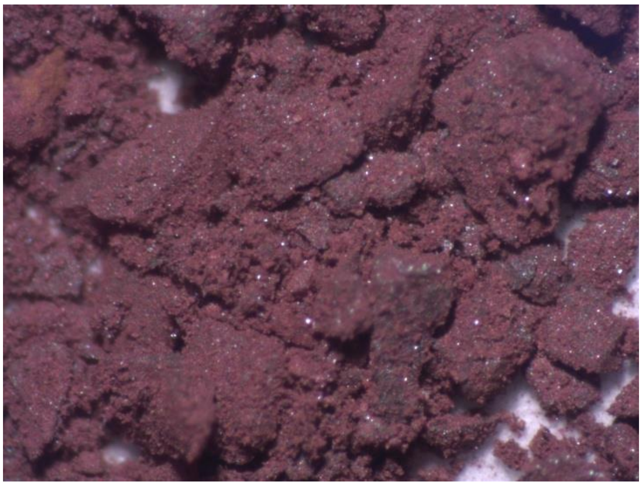


Figure 1 - Hematite feed sample

The sample was blended and a representative sample taken out for particle size distribution (PSD) determination and size by assay. The results are shown in Table 1.

Table 1 - Feed sample size by assay

Size (microns)	% Mass	Cumm % Retained	% Fe	Cumm % Fe	% Fe Recovery	Cumm % Fe Recovery	% SiO_2	Cumm % SiO_2	% SiO_2 Recovery	Cumm % SiO_2 Recovery
+										
1000	7.80	7.80	39.60	39.60	8.23	8.23	41.72	41.72	7.49	7.49
850	12.71	20.52	38.37	38.84	12.99	21.22	43.18	42.62	12.63	20.11
600	19.85	40.36	37.73	38.30	19.95	41.17	44.02	43.31	20.10	40.21
425	13.91	54.28	36.38	37.81	13.48	54.66	45.88	43.97	14.68	54.89
300	10.97	65.25	36.32	37.56	10.62	65.27	45.99	44.31	11.61	66.50
212	8.11	73.36	35.63	37.34	7.70	72.97	47.00	44.61	8.77	75.27
150	5.10	78.46	36.01	37.26	4.89	77.86	46.11	44.70	5.41	80.68
106	4.37	82.83	36.44	37.21	4.24	82.11	45.46	44.74	4.57	85.25
75	2.87	85.71	37.13	37.21	2.84	84.95	44.00	44.72	2.91	88.16
53	1.90	87.61	37.98	37.23	1.93	86.88	41.91	44.66	1.84	89.99
38	1.46	89.07	39.11	37.26	1.52	88.39	39.83	44.58	1.34	91.33
	10.93	100.00	39.85	37.54	11.61	100.00	34.49	43.48	8.67	100.00
	100.00		**37.54**		**100.00**			**43.48**	**100.00**	

Method

The test work was conducted on the Multotec SC20HC spiral fitted with a mouth organ product box as shown in Figure 2. Mouth organ (MO) fraction A represents the sample collected from the inside of the trough. It is the heaviest sample and should contain most of the Fe.

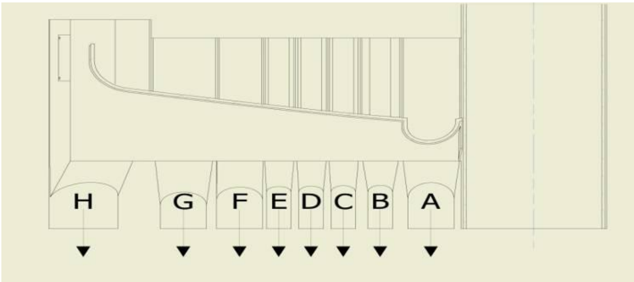


Figure 2 - Mouth organ configuration

The spiral was operated in closed circuit as shown in Figure 3. The slurries were fed to the spiral feed box via a distributor with an overflow to ensure constant feed conditions during the test.

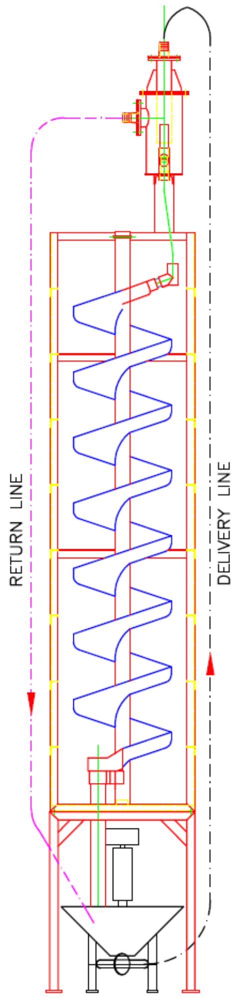


Figure 3 - Spiral test rig setup

Each spiral stage was run until steady state conditions were reached before taking the relative density (RD), solids concentration and feed rate measurements at the top of the spiral rig. Three consistent RD measurements and three consistent flow rate measurements were recorded before taking simultaneous timed samples (fractions A to H) from the mouth organ.

Figure 4 shows the setup of the open trough drip wash water system. The spiral is equipped with 4 wash water nozzles which are positioned before the sliding splitters. The wash water nozzles are setup such that the water drips onto the concentrate material closest to the center column before the sliding splitter. The flow of the wash water is concurrent with the slurry flow on the spiral.

Figure 4 - Wash water setup

The spiral was first tested at 30%, 35% and 40% solid concentrations using the iron ore sample without wash water; this was done to establish a benchmark against which the effect of wash water would be compared. Each test was done 3 times to check reproducibility of each test. The effect of wash water using the drip system was tested at various solids concentration at a total wash water rate of 5l/min, off the 5l/min introduced on the spiral only 1l/min was utilized for the washing on the spiral. There are four wash water nozzles on the spiral; each nozzle used about 250ml of water. The tests were again done 3 times. The sliding splitters settings remained unchanged throughout the program and the solid feedrate was kept constant at 2tph. The mouth organ product samples from each spiral test were collected and analyzed by ICP method for Fe and SiO_2 content. The test work and chemical analysis data were used to calculate the mass yield and the corresponding Fe and SiO_2 grade and recoveries. The test plan used and a summary of results obtained is shown in Table 2.

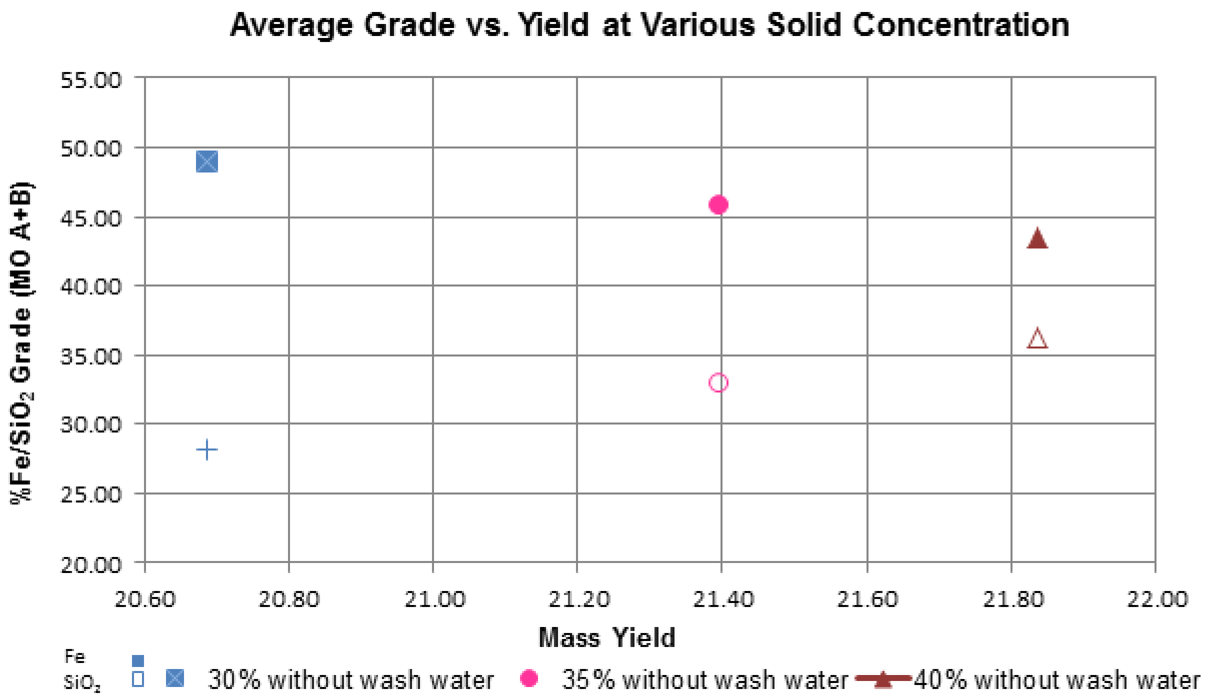
Table 2 - Test plan and summary of results

Test	Test Parameters			Recon Feed Grade		Concentrate	Concentrate Grade		Concentrate Recovery	
	% Solid concentration w/w	Wash water l/min	Solid feedrate tph	% Fe	% SiO_2	% Mass yield	% Fe	% SiO_2	% Fe	% SiO_2
1	30	5	2	34.54	48.07	10.30	50.64	25.61	15.13	5.50
2	30	5	2	33.13	49.91	14.80	49.53	27.43	22.12	8.13
3	30	5	2	35.39	49.68	11.66	51.28	24.59	17.91	5.77
Ave	**30**	**5**	**2**	**34.35**	**49.22**	**12.25**	**50.48**	**25.88**	**18.39**	**6.47**
4	30	0	2	35.10	47.30	22.27	45.02	33.77	28.57	5.50
5	30	0	2	35.89	46.18	21.31	50.34	26.36	29.89	12.16
6	30	0	2	36.67	45.28	18.48	51.77	24.46	26.09	9.99
Ave	**30**	**0**	**2**	**35.89**	**46.25**	**20.69**	**49.04**	**28.20**	**28.18**	**9.22**
7	35	5	2	36.36	45.31	8.37	52.45	23.19	12.08	13.46
8	35	5	2	34.03	49.34	9.62	50.45	26.05	14.26	5.08
9	35	5	2	36.59	45.30	11.21	51.31	24.99	15.71	6.18
Ave	**35**	**5**	**2**	**35.66**	**46.65**	**9.73**	**51.40**	**24.74**	**14.02**	**8.24**
10	35	0	2	34.51	48.07	18.80	44.55	34.40	24.27	13.46
11	35	0	2	37.90	43.81	20.84	47.99	29.80	26.39	13.46
12	35	0	2	36.92	45.25	24.55	44.70	34.72	29.73	18.84
Ave	**35**	**0**	**2**	**36.44**	**45.71**	**21.40**	**45.75**	**32.97**	**26.80**	**15.25**
13	40	5	2	33.92	49.38	13.12	51.42	24.93	19.89	6.62
14	40	5	2	36.79	45.21	16.09	46.67	31.70	20.40	11.28
15	40	5	2	35.04	47.08	10.72	54.04	20.97	16.42	4.78
Ave	**40**	**5**	**2**	**35.25**	**47.22**	**13.31**	**50.71**	**25.87**	**18.90**	**7.56**
16	40	0	2	36.42	46.14	23.74	39.91	41.62	26.01	21.41
17	40	0	2	36.22	46.06	20.44	46.88	31.39	26.46	13.93
18	40	0	2	37.00	45.04	21.34	43.77	35.89	25.24	17.00
Ave	**40**	**0**	**2**	**36.55**	**45.75**	**21.84**	**43.52**	**36.30**	**25.90**	**17.45**

RESULTS

Effect of Solid Concentration on Grade

Figure 5 shows the effect of solid concentration on grade and mass yield



.

Figure 5 - The effect of various solid concentrations on grade

The average results at 30% solid concentration shows that the sample was upgraded from 35.89% to 49.04% Fe in the concentrate fraction; this was achieved at a mass yield of 20.69%. The %SiO_2 was downgraded from 46.25% to 28.20%.

The average results at 35% solid concentration shows that the sample was upgraded from 36.44% to 45.71% Fe in the concentrate fraction; this was achieved at a mass yield of 21.40%. The %SiO_2 was downgraded from 45.71% to 32.97%.

The average results at 40% solid concentration shows that the sample was upgraded from 36.55% to 43.52% Fe in the concentrate fraction; this was achieved at a mass yield of 21.84%. The %SiO_2 was downgraded from 45.71% to 36.30%.

The results suggest that the lower the solid concentration the better the upgrade and that the Fe grade in the concentrate reduces as solid concentration increases, similarly the SiO_2 downgrade is best at the lowest solid concentration and decreases as solid concentration increases. As can be expected at high solid concentration, there is more particle interaction and high gangue entrapment. The mass yield to the concentrate on the other hand increases with an increase in solid concentration.

Effect of Wash Water on Grade

Figure 6 shows the effect of wash water on grade at 30% solid concentration with and without the use of wash water.

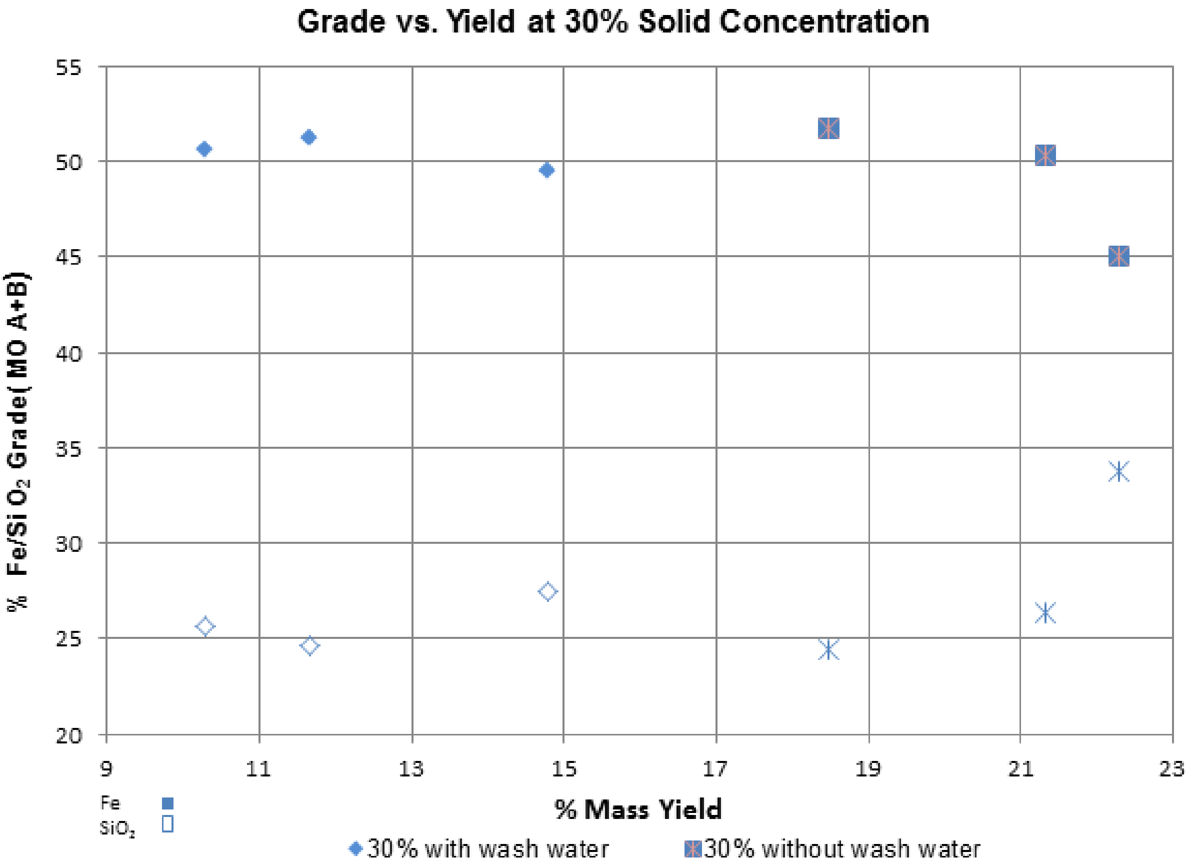


Figure 6 - The effect of wash water on grade at 30% solid concentration

The average concentrate grade achieved at 30% solid concentration with wash water is around 50.58% Fe and 25.88% SiO_2; this was achieved at a mass yield of 12.25%. The results for the test without wash water show an average of 49.04% Fe and 28.20% SiO_2 in the concentrate at a mass yield of 20.69%.

There is no significant difference between the Fe grade in the concentrate (MO A+B) obtained with and without wash water at 30% solid concentration, the upgrades are similar. The wash water only improved the Fe grade on average by approximately 1.5% in the concentrate. The additional SiO_2 rejected by the wash water is approximately 3%. The results suggest that at 30% solid concentration the slurry is dilute enough to reduce entrapment of SiO_2. Addition of water mainly results in reduction of mass yield to the concentrate.

Figure 7 compares the grade/yield results obtained at 35% solid concentration with and without the use of wash water.

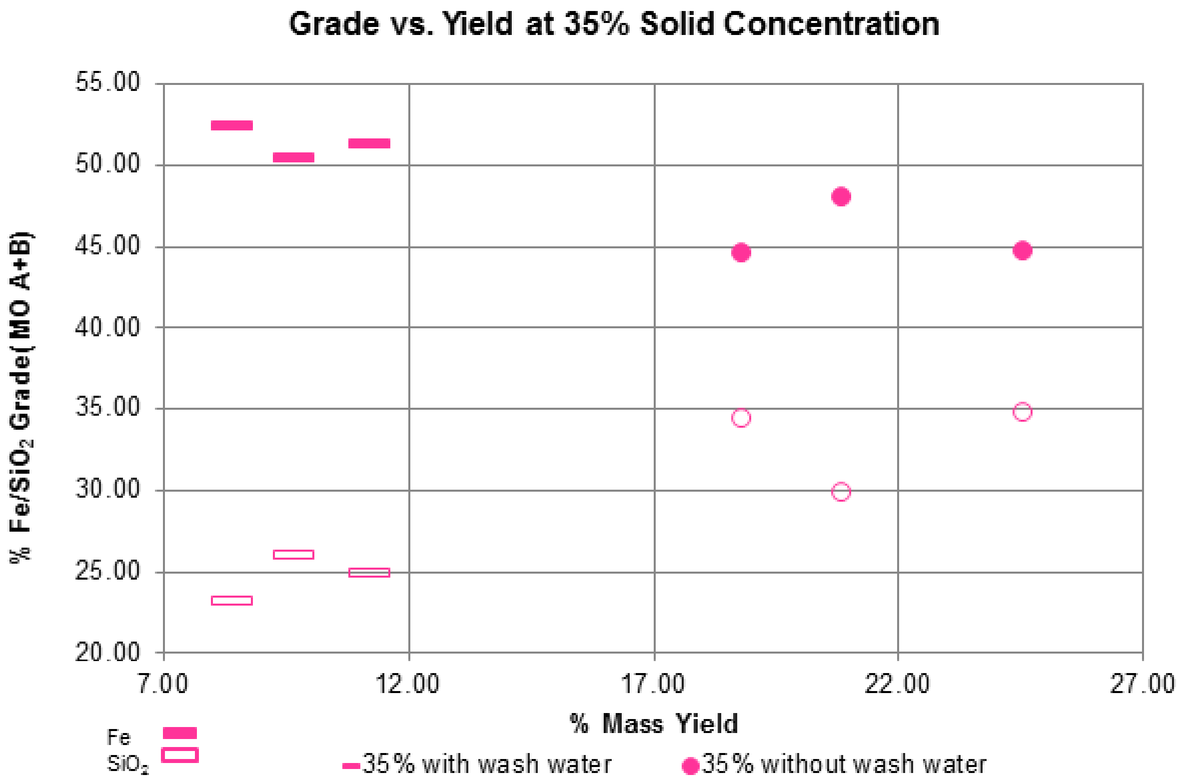


Figure 7 - The effect of wash water on grade at 35% solid concentration

The average concentrate grade achieved at 35% solid concentration with wash water is around 51.40% Fe and 24.74% SiO_2; this was achieved at a mass yield of 9.73%. The results for the test without wash water show an average of 45.75% Fe and 32.97% SiO_2 in the concentrate at a mass yield of 21.40%.

The use of wash water at 35% solid concentration improved the Fe grade in the concentrate (MO A+B) by about 6%. The additional SiO_2 rejected by the wash water is nearly 9%. This is double the rejection obtained at 30% solid concentration, the results elude that as solid concentration increases, the mean free path for particles is reduced and that the SiO_2 entrapment increases as a result. The addition of wash water therefore fluidises the bed of particles on the trough and assists in alleviating the SiO_2 entrapment. The additional washing away of SiO_2 as expected comes at an expense of mass yield.

Figure 8 compares the grade/yield results obtained at 40% solid concentration with and without the use of wash water.

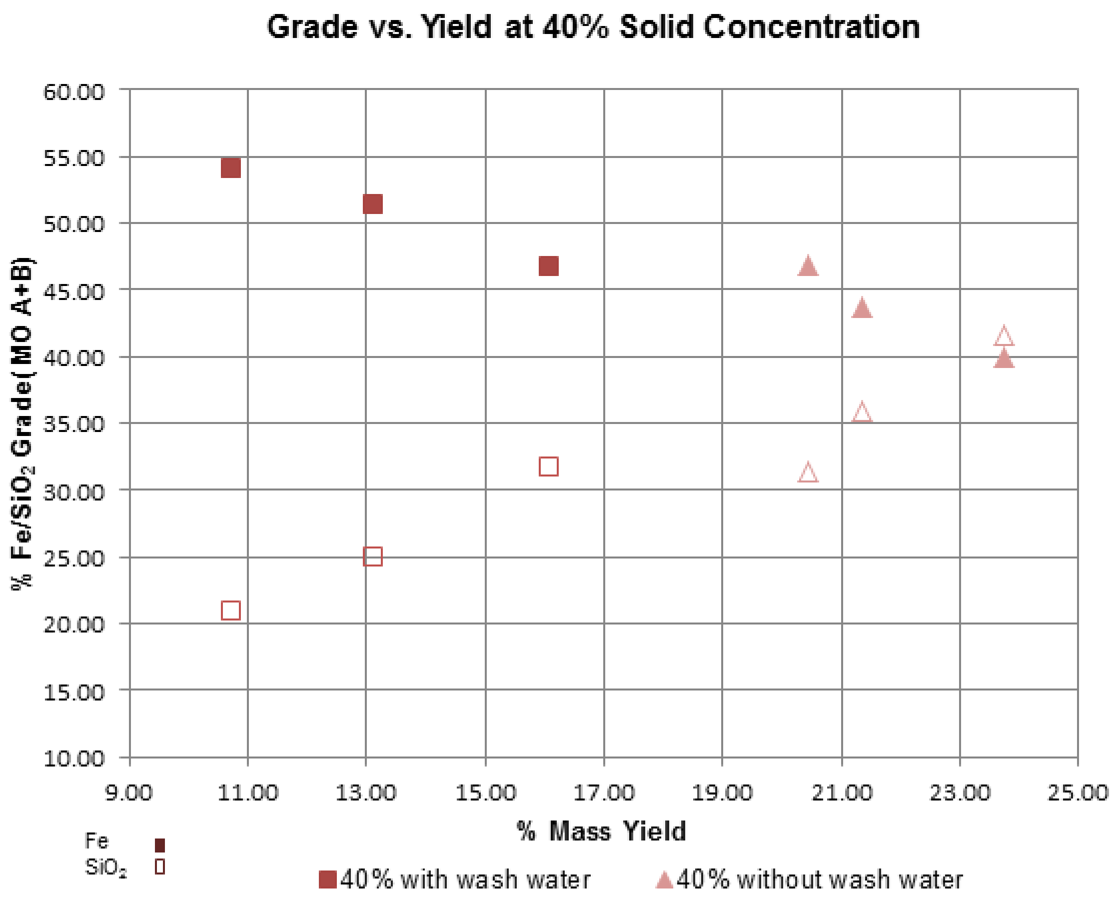


Figure 8 - The effect of wash water on grade at 40% solid concentration

The average concentrate grade achieved at 40% solid concentration with wash water is around 50.71% Fe and 25.87% SiO_2; this was achieved at a mass yield of 13.31%. The results for the test without wash water show an average of 43.52% Fe and 36.30% SiO_2 in the concentrate at a mass yield of 21.84%.

The use of wash water at 40% solid concentration improved the Fe grade in the concentrate (MO A+B) by about 8%. The additional SiO_2 rejected by the wash water is nearly 11%. As expected addition of water washes away Fe along with SiO_2 and hence lower mass yields are obtained with the use of wash water.

Effect of wash water on Fe and SiO_2 recovery

Figure 9 shows the effect of solid concentration on recovery of Fe and SiO_2 and mass yield without wash water.

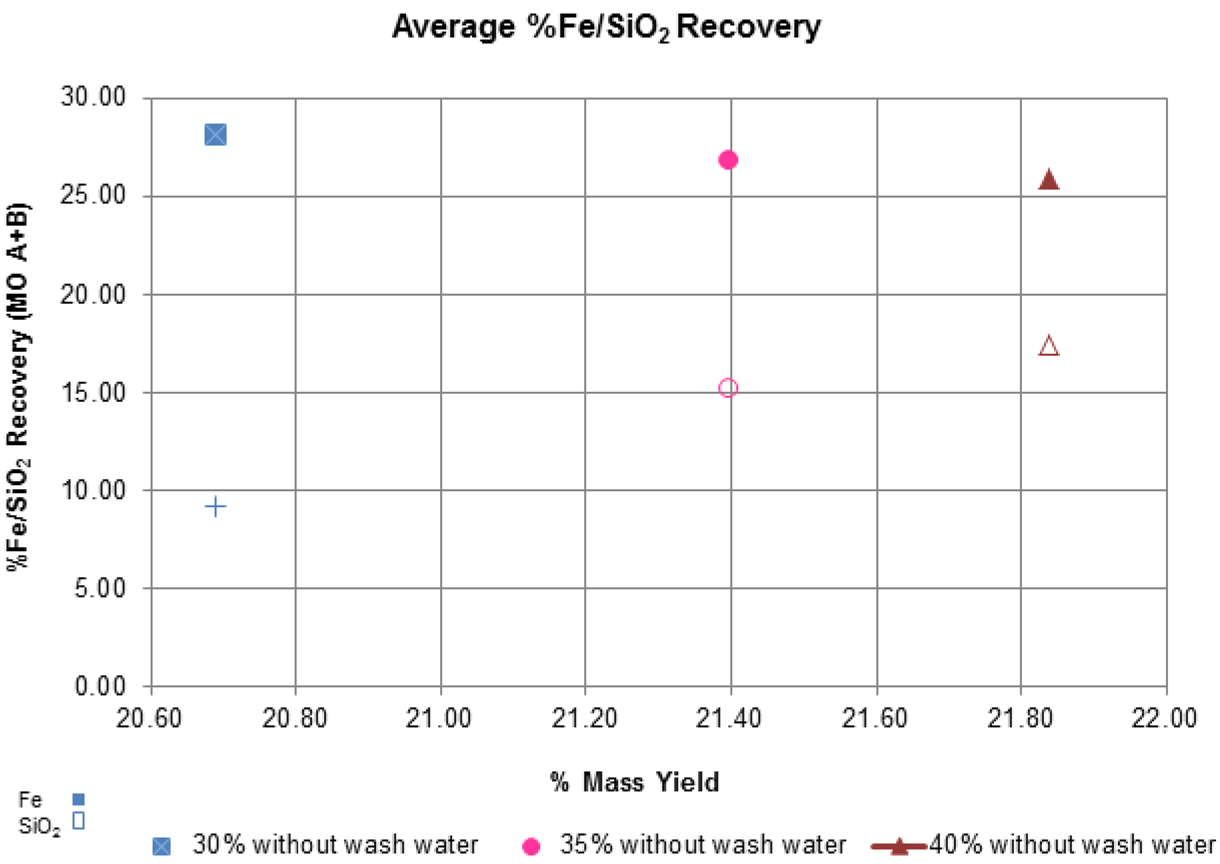


Figure 9 - The effect of various solid concentrations on grade

The recovery of Fe achieved in the concentrate at 30%, 35%, and 40% solid concentration without wash water is 28.18%, 26.80%, and 25.90% respectively.

The recovery of SiO_2 achieved in the concentrate at 30%, 35%, and 40% solid concentration without wash water is 9.22%, 15.25%, and 17.45% respectively.

As with the grade/yield relationship, the recovery of Fe is the highest at the lowest solid concentration and decreases as solid concentration increases. The SiO_2 relationship is the inverse of Fe relationship; it is the lowest at low solid concentration and increase with an increase in solid concentration.

Figure 10 shows the effect of various solid concentrations and wash water on recovery of Fe and SiO_2 and mass yield.

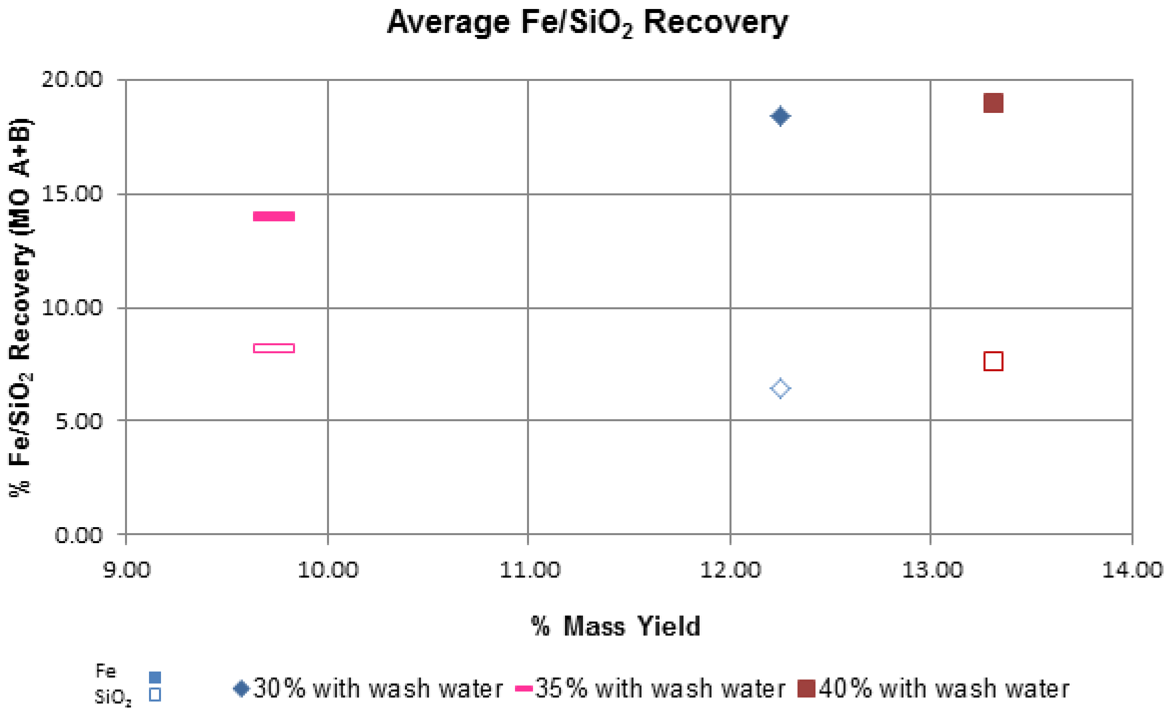


Figure 10 - The effect of various solid concentrations and wash water on recovery

The recovery of Fe achieved in the concentrate at 30%, 35%, and 40% solid concentration with wash water is 18.39%, 14.02%, and 18.90% respectively.

The recovery of SiO_2 achieved in the concentrate at 30%, 35%, and 40% solid concentration with wash water is 6.47%, 8.24%, and 7.56% respectively.

The results show that the recovery is the lowest at 35% solid concentration with the use of wash water, then increases at 30% solid concentration and is the highest at 40% solid concentration. The results suggest that the relationship between solid concentration and recovery with addition of wash water is not linear. Figure 11 shows a different representation of the same results, with both grade and recovery at various solid concentrations.

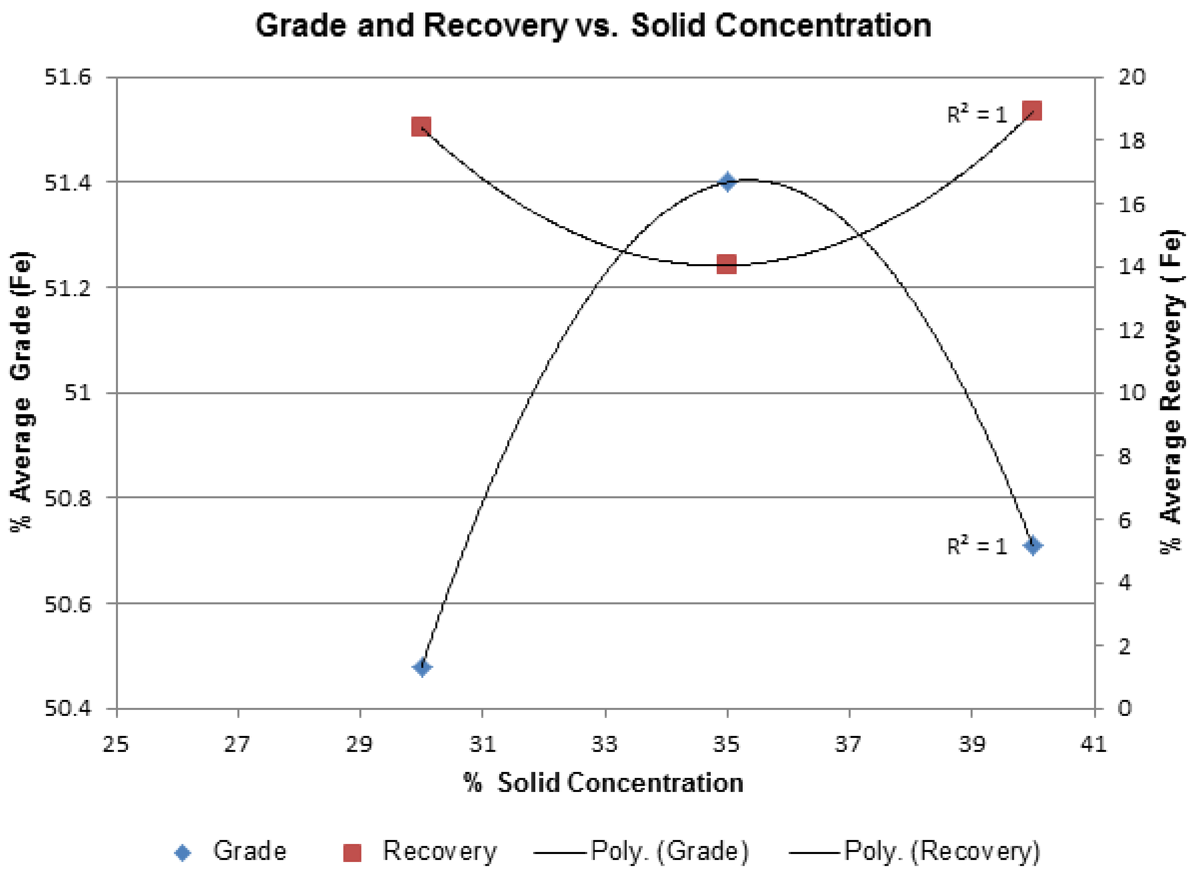


Figure 11 - The effect of various solid concentration and wash water on grade and recovery

Figure 11 suggests that the grade increases with an increase in solid concentration up to an optimum point and then drops as solid concentration increases further. The recovery of Fe on the other hand follows a converse relationship with solid concentration, the recovery decreases up to 35% solid concentration and then increases again at 40% solid concentration. The corresponding grade at 40% solid concentration is lower, since recovery is a function of both grade and mass yield the higher recovery at 40% solid concentration is possibly due to the high mass yield obtainable at 40% solid concentration.

CONCLUSIONS

The study investigated the effect of the wash water drip system on a spiral with the grade and recovery of Fe and SiO_2 measured as a response. The Multotec SC20HC spiral fitted with the wash water drip system was used for all the tests. The spiral was tested at 30%, 35% and 40% solid concentrations with and without wash water using an iron ore sample.

The tests without wash water upgraded the material in the following manner:

- At 30% solid concentration the sample was upgraded from 35.89% to 49.04% Fe in the concentrate fraction; this was achieved at a mass yield of 20.69%. The %SiO_2 was downgraded from 46.25% to 28.20%.

- At 35% solid concentration the sample was upgraded from 36.44% to 45.71% Fe in the concentrate fraction; this was achieved at a mass yield of 21.40%. The %SiO_2 was downgraded from 45.71% to 32.97%.

- At 40% solid concentration the sample was upgraded from 36.55% to 43.52% Fe in the concentrate fraction; this was achieved at a mass yield of 21.84%. The %SiO_2 was downgraded from 45.71% to 36.30%.

- The recovery of Fe achieved in the concentrate at 30%, 35%, and 40% solid concentration is 28.18%, 26.80%, and 25.90% respectively.

- The recovery of SiO_2 achieved in the concentrate at 30%, 35%, and 40% solid concentration is 9.22%, 15.25%, and 17.45% respectively.

The relationship between Fe grade/recovery and mass yield at various solid concentrations without the wash water shows a linear relationship with the Fe grade and recovery being the highest at the lowest solid concentration and decreasing as the solid concentration increased. The SiO_2 relationships are the inverse of Fe, and the relationships increased with an increase in solid concentration. The mass yield in the concentrate also increases with an increase in solid concentration.

The tests with wash water upgraded the material in the following manner:

- At 30% solid concentration the sample was upgraded from 34.35% to 50.48% Fe in the concentrate fraction; this was achieved at a mass yield of 12.25%. The %SiO_2 was downgraded from 49.22% to 25.88%.

- At 35% solid concentration the sample was upgraded from 35.66% to 51.31% Fe in the concentrate fraction; this was achieved at a mass yield of 9.73%. The %SiO_2 was downgraded from 46.65% to 24.74%.

- At 40% solid concentration the sample was upgraded from 35.25% to 50.71% Fe in the concentrate fraction; this was achieved at a mass yield of 13.31%. The %SiO_2 was downgraded from 47.22% to 25.87%.

- The recovery of Fe achieved in the concentrate at 30%, 35%, and 40% solid concentration is 18.39%, 14.02%, and 18.90% respectively.

- The recovery of SiO_2 achieved in the concentrate at 30%, 35%, and 40% solid concentration is 6.47%, 8.24%, and 7.56% respectively.

The use of wash water at 30%, 35% and 40% solid concentration improved the Fe grade in the concentrate (MO A+B) by about 1.5%, 6%, and 8% respectively. The additional SiO_2 rejected by the wash water is approximately 3%, 9%, and 11% at 30%, 35% and 40% solid concentration respectively. Addition of wash water is shown to have minimum effect on grade at 30% solid concentration, Fe upgrades obtained with and without wash water were found to be similar. Notable upgrades were observed at 35 and 40% solid concentration with wash water. The results obtained suggest that the additional SiO_2 rejection by wash waters increases with an increase in solid concentration. This suggests that the benefit of using the drip system is notable at higher solid concentration. It is believed that at lower solid concentration SiO_2 particles are reasonable free to move around and are possibly less entrapped than at high solid concentration.

The Fe grade/recovery and solid concentration relationship with wash water showed a non-linear correlation. The Fe grade increases with an increase in solid concentration up to somewhat optimum point and then drops as solid concentration increases further. The recovery of Fe on the other hand follows a converse relationship with solid concentration, the recovery decreases from 30% to 35% solid concentration and then increases again at 40% solid concentration. The increase in recovery at higher solid concentration could possibly be explained by the fact that the mass yield to concentrate also increases with solid concentration. Since recovery is a function of both grade and mass yield, the higher recovery at 40% solid concentration is likely due to the high mass yield obtainable at 40% solid concentration.

As with any wash water system, in addition to gangue rejection adding water comes with a sacrifice in mass yield and somewhat recovery of valuable minerals as well. The amount of wash water used for washing also has an effect on the losses of valuable minerals, a good balance between the wash water and gangue rejection is therefore important. The lower the amount of wash waters the better. The drip system wash water offers the option to use low volumes of water; 5l/min is used for the system in total. There are 4 nozzles in total on the spiral, and the washing through the drip nozzles is about 1l/min (250ml/nozzle) while that of the high wash water system typically ranges between 10l/min to about 21l/min. The drip system could therefore possibly offer a safe guarding against grade and solid concentration variations without using excessive water, and possibly ensure that a product within specification is maintained.

RECOMMENDATIONS

A direct comparison between the drip system and the high flow wash water system should be conducted on the same sample to evaluate the differences between the two systems and to establish whether the drip system can offer similar results and if it offers a better alternative at low wash water rates.

ACKNOWLEDGEMENTS

The authors are grateful to Anglo-American (Kumba Iron Ore Resources) for providing the ore for the experimental work and to Multotec Process Equipment for all the resources that enabled this work.

REFERENCES

Atasoy, Y., and Spottiswood, D.J. (1995). A study of particle separation in a spiral concentrator. *Minerals Engineering, Vol 8, No. 10,* 1197-1208.

Bazin, C., Sadeghi, M., Bourassa, M., Roy, P., Lavoie, F., Cataford, D., Rochefort, C., and Gosselin C.(2014). Size recovery curves of minerals in industrial spirals for processing iron oxide ores. *Minerals Engineering, No. 65,* 115-123.

Boucher, D., Deng, Z., Leadbeater, T., Langlois, R., Renaud, M., and Waters K.E. (2014). PEPT studies of heavy particle flow within a spiral concentrator. *Minerals Engineering, No. 62,* 120-128.

Holland-Batt, A.B. (2009). A method for the prediction of the primary flow on large diameter spiral troughs. *Minerals Engineering, No. 22,* 352-356.

Holland-Batt, A. B. (1995). Some design considerations for spiral separators*, Minerals Engineering, Vol.8, No. 1/2*, 3-21.

Holland-Batt, A. B. (1994). The dynamics of sluice and spiral separators, *Minerals Engineering, Vol.8, No. 11*, 1361-1390.

Holland-Batt, A.B., and Holtham, P.N. (1991). Particle and fluid motion on spiral separators. *Minerals Engineering, Vol 4, No. 3/4,* 457-482.

Holland-Batt, A. B. (1990). Interpretation of spirals and sluice tests, Institution of Mining and Metallurgy (Section C: Mineral Process .Extr. Metall), Vol 99, C11-20.

Holtham, P.N. (1992). Particle transport in gravity concentrators and the Bagnold effect. *Minerals Engineering, Vol 5, No. 2,* 205-221.

Holtham, P.N. (1990). Flow visualization of secondary currents on spiral separators. *Minerals Engineering, Vol 3, No. 3/4,* 279-286.

Hyma, D.B., and Meech, J.A. (1989). Preliminary tests to improve the iron recovery from the -212 micron fraction of new spiral feed at Quebec Cartier Mining Company. *Minerals Engineering, Vol 2, No. 4,* 481-488.

Kapur, P. C., & Meloy T. P. (1998). Spirals observed, International Journal of Mineral Processing, Vol.53, 15-28.

Ramotsabi, C. M.,Erasmus W. & Bornman, F. (2015). Wash water optimization on an iron ore spiral. *Proceedings of the 47th Annual Canadian Mineral Processors Operators Conference, Ottawa, Ontario.*

Reddy, R., Kruger, L., Ramotsabi, C. M., & Lincoln, D. (2010). Iron ore beneficiation using the SC20HC spiral. *Proceedings of the Southern African Institute of Mining and Metallurgy Fines Beneficiation and de-watering and agglomeration,* 13-29.

Richards, R. G., & Palmer M. K. (1997). High capacity gravity separators- A review of current status, *Minerals Engineering, Vol.10, No.9*, 973-982.

Pascoe, R.D., Power, M.R. and Simpson B. (2007). QEMSCAN analysis as a tool for improved understanding of gravity separator performance. *Minerals Engineering, No. 20,* 487-495.

Sadeghi, M., Bazin, C. and Renaud M. (2014). Effect of wash water on the mineral size recovery curves in a spiral concentrator used for iron ore processing. *International Journal of Mineral Processing, 129,* 22-26.

FIGURE CAPTIONS

TABLE CAPTIONS