The evolution of spirals in the coal fine circuit: a review

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Abstract. Spiral concentrators are extensively employed in coal beneficiation for the processing of fine coal particles within the size range of 2000 to 100 microns. Spirals separate valuable minerals from gangue based on their density. Among the gravity separators, the spiral concentrator is one of the most efficient and simple unit operations. The main operating variables for a spiral concentrator are the feed rate, the solid concentration, and the position of the cutters or splitters used to separate the tailings, middling and concentrate streams. Traditional spirals are classified as high-cut technologies with typical cut point between 1.7 and 1.8 specific gravity. Recent developments in spirals have seen the introduction of low-cut spirals to the markets, these spirals have been shown to produce specific gravity cut points in the range of 1.4 to 1.55. This paper aims to review the status of spiral development, understand current challenges associated with fines processing in the industry and to establish gaps that require addressing to make the spiral relevant in the fines circuit while solving challenges faced in the coal processing industry.

1 Introduction

Coal is one of the most prevalent and significant fossil fuels used globally. It is a solid, combustible substance rich in carbon. The saleable coal produced in SA is supplied to four main markets which include the global export market, the domestic synfuels market, the domestic energy supply, and for domestic heating and industrial use. These markets are reported to consume about 27%, 18%, 46% and 9 % of the saleable coal produced in South Africa respectively [1]. Each sector has unique needs in terms of sizing and quality of coal. As a result, various preparation levels and distinct coal preparation plant designs are required.

Typically, run-of-mine (ROM) is mined, screened and processed in a Dense Medium Separation DMS circuit. The DMS is usually applied to the coarse size fraction, +1mm. According to reports, 15% of most South African ROM is made up of fine material below 0.5mm [2]. The production of fine coal has grown due to automated mining techniques. According to reports, this percentage has increased to almost 30% in recent years [3].

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In the past, run-of-mine (ROM) coal smaller than 0.5 mm in South Africa was typically either stockpiled, discarded in tailings dams, or blended untreated with the washed product—practices that continued until recently [4, 5]. Treating and recovery of finer coal has an economical and environmental benefit. Recovery of finer fractions enhances better utilization of coal and increases the production output. If finer material is recovered this minimizes the amount of material that is sent to the tailings dam and indirectly lessens the environmental risks associated with untreated coal [6]. Although there is value in the finer fraction, beneficiation is not always easy. There are limitations in what the available technologies can do, often a combination of these fine beneficiation technologies is utilized for optimal recovery of coal [5].

The most common processes utilised in fine coal beneficiation are spirals, flotation, dense medium separation (DMS), water only cyclones, teeter beds and classifiers [5]. Spirals, teeter beds and classifiers are primarily used for cleaning coal in the intermediate size range of 100µm to 2000µm. These coal particles are neither large enough for heavy media separation and nor small enough for froth flotation [7]. Flotation is usually performed on material below 200micron, if flotation is not feasible material below this size range ends up in the tailings dam.

The discard from processing plants is usually pumped to tailing dams. Due to process equipment inefficiencies or limitations some coal is also discarded with the waste. Coal particles contained in these tailing dams can be a cause of environmental issues. If tailing dams are not lined, some heavy metals including sulphates, nitrates and chlorides contained in the coal particles if present in significant quantities can cause Acid Mine Drainage and consequently contaminate the surrounding soil, rivers and ground water. The coal can also be a source of self-ignition and explosion. When coal burns, harmful gases are released to the atmosphere causing pollution. Therefore, it is evident that the continuous enhancement of beneficiation technologies is essential for efficient recovery of fines as this ensures better utilization of coal, adds additional revenue to operations and lessens the environment impact [6].

2 Spirals

Spirals concentrators are process equipment used for beneficiation of minerals. Spirals separate valuable minerals from gangue based on their density. Among the gravity separators, the spiral concentrator is one of the simplest unit operations which is widely used under a variety of circuit configurations for processing of minerals and coals [8]. The spiral is known to be tolerable to high variation in feed conditions. The capital cost is relatively low compared to other technologies and the operational costs are also minimal [5].

Spirals are low maintenance, however regular washing and checking of blockages and process control is required to ensure that they are not overfed. They are usually neglected in the plant and get used as ladders. Deviation from ideal operating conditions can negatively impact the separation efficiency of spirals, resulting in a high cut point and lower product quality [5].

2.1. Separation mechanism

Separation in a spiral is not only dependent on the density of the particles but also on the size of the particles. The bigger particles are affected more than smaller particles. Therefore, gravity concentration efficiency increases with an increase in particle size. To ensure efficient separation desliming is required. Since coal has a significant ash concentration below 100microns, anything less than 100 microns is regarded as slimes [5].

2.2. Design and operational parameters

The performance of the coal-processing spiral is a critical function of its design parameters, which include diameter, height, number of turns, pitch, slope, shape of the trough and its dimension. Holtham [9] found the flow can be considered to be fully developed after at most two turns. Studies have also shown that feed rate, especially the total volumetric flow greatly affects its performance and is among the critical factors for determining coal spiral capacity. Investigations [10] show that, for any feed pulp density there exists an optimum feed rate. Studies [11] indicate that the spiral performance is considerably affected by slurry density and that a more dominant control is observed when combining the slurry with the solid flow rate. Based on a typical coal cleaning application, spirals effectively treat between 2 and 3 tph per start at a recommended solid concentration of 30% by weight [12].

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 wash waterless spiral can prevent further separation of particles. This necessitates the use of splitters to remove the material that has already separated from the trough before they start to beach. Continuous removal of the concentration along the length of the spiral provides more area for further separation. The reduced fluidity in the inner region of the trough can be restored by employing repulpers. Repulpers spray back the dilute material from the outside of the trough in a shallow fan over the inner part of the trough. This also provides the misplaced heavy mineral on the outside of the trough with another chance of separation. Removal of product followed by employing a repulper to spray back the dilute material from the outside of the trough over the inner part of the trough was shown to be effective in restoring the initial higher rate of recovery. Efficiency at the same mass yield increases by 5-6% and similar gains have been recorded on many other spirals and feed types. Repulpers are, however, considered to be counter-productive on the coal spiral, they decrease the recovery of coal. The repulping action is said to be detrimental to recovery since coal is less dense and it concentrates on the outside of the trough, spraying back dilute material from the outside of the trough results in relocation of the already separated coal product to the reject stream [10].

Contrary to the above findings, studies with a repulper used as a mixing box on the SX7 spiral has been shown to enhance a product grade of coal, the use of the repulper in this case enabled a single spiral start to be utilized as a spiral that does both primary and secondary stages [13]. The repulper and the splitter on the SX7 spiral play a vital role in determining the final product ash. The splitter separates the material after the 3rd turn into two streams: high ash and low ash streams. The high ash stream is channeled into the center column while the low ash is directed into the repulper. The material in the center column is collected at the end of the spiral trough as a reject fraction. The low ash fraction on the other hand is mixed again in the repulper and given a second chance for further rejection of ash [14].

2.3. Low cut spirals

The fine coal processing sector in South Africa has been using low-cut spirals and classifiers more frequently in recent years. This is particularly evident in wash operations that export low ash products and provide the national electricity provider with a secondary thermal product. It has been demonstrated that every technology has pros and cons for processing fine coal [15]. Selection of one over the other among others is usually dictated by market specifications and coal geometallurgy. Where high quality coal products are required a technology with a lower SG cut point capability is required to achieve such a product. For a long time for these applications classifiers were usually the preferred choice over spirals.

Classifier separators provide variable cut densities, however if higher product qualities are targeted the discard from these technologies have been shown to still contain valuable coal [5].

Low-cut spirals have been introduced to the marketplace because of recent advancements in spirals. One of the low-cut designs developed by Mineral technologies is called the LC3 spiral and was introduced in 2013[16]. This spiral has a distinctive trough design and offers a unique flow regime where a precise gravity profile forms throughout the particle bed. Compared to conventional spiral designs, lower cut points are made possible by this shift in density profile [17]. A new, gentler flow regime is produced by the LC3 design, which dampens flow energy and lowers turbulence. This idea was difficult since the separation mechanism also needs the pulp bed to remain continuously mobile and fluid. To overcome this difficulty, the LC3 was created using a dynamic set of pitches and profiles that gradually adjust for the slurry's shifting characteristics as it travels down the trough. There is a shorter four-turn version of the LC3, but the regular LC3 is an eight-turn spiral. Figure 1 below shows a picture of the LC3 spiral [18].

Fig. 1. LC3 low-cut spiral [18]

It is reported that the spiral can achieve cut points around 1.4 and 1.55, which are lower than traditional models [16]. To demonstrate the performance, the LC3 spiral was compared to the LD7RC spiral. The LD7RC is one of the conventional spirals. This test work was done using a spiral feed sample from Queensland, Australia [16]. The results for each of the spirals are shown in the charts in Figure 1 below.

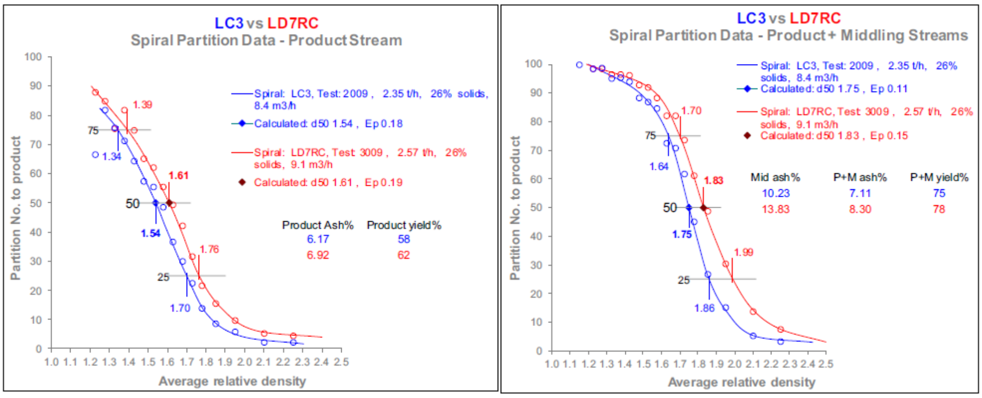

Fig. 2. LC3 vs LD7RC [16]

Both models produced low product ash grades and showed promising metallurgical performances. In the product and middling streams, the LC3 obtained reduced ash grades. At both the lower and higher specific gravity cut points (1.54 and 1.75 respectively), the LC3 showed better separation than the LD7RC.

In another study Ramsaywok and Mathumbu [19] demonstrated that the LC3 spiral can achieve a lower ash product compared to conventional spirals. Figure 3 shows the grade yield relationship on the testwork done. The testwork was done on a South African coal sample in a laboratory setting.

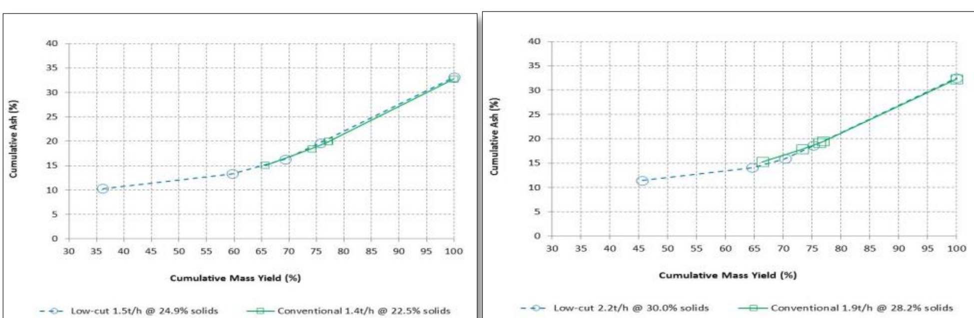

Fig. 3. LC3 spiral vs the conventional spiral [19]

The grade recovery lines of the two spirals are comparable at 1.5 t/h and 25% solids; however, the conventional spiral did not permit any splits in a single pass to create an ash product below 15%. At an ash quality below 15%, the yield was reduced on the LC3 spiral. This finding holds true for each of the experiments that were conducted.

The LC3 spiral is also reported to be able to process and recover ultrafine coal down to 40 microns, which would ordinarily land at a tailings dam if not processed by flotation. Historically, spirals have been unable to process ultrafine material primarily because the small particles are carried at high velocity in the spiral's radial wave front, which prevents the particles from separating based on density. This effectively results in misplacement of ultrafine material in the spiral's product, regardless of the particle density. The flow is less turbulent and better distributed throughout the spiral due to the LC3's concentric wave pattern profile rather than radial wave front, which gives the ultrafine particles a chance to beneficiate rather than primarily report to the product.

Another low-cut spiral introduced in the market is the SX10 spiral designed by Multotec. The SX10 spiral is a 10 turn, 1000mm diameter spiral, equipped with 2 repulpers positioned at the 4^{th} and 7^{th} turn, making it a 3 stage in 1 low-cut spiral. This spiral is an extension of the SX7 spiral which has been long in operation as a traditional spiral, the difference between the two spirals is the additional repulper and 3 turns which increases the retention time [15, 20]. Figure 4 gives a portrayal of the SX10.

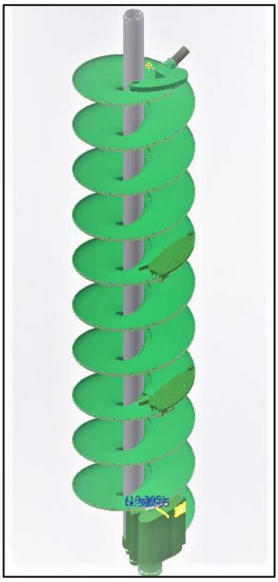

Fig. 4. SX10 low-cut spiral [15]

The SX10 has 2 offtakes that direct the discard into the auto reject center column. The offtakes are there to remove portions of the discard that have been separated from the working surface on the spiral. This increases the surface area available for separation and allows more material to be processed without excessively increasing particle crowding on the spiral. With more of the undesired material removed higher up the spiral, the reduced solids loading and solid concentration of the material lower down the length of the spiral creates a favorable environment for a low-cut product to be achievable. The offtakes are positioned before the repulpers. This ensures that once a portion of the discard is removed, while the material remaining on the spiral is mixed again by the repulper.

In another study, Arnold *et al.* [20] showed that the Multotec SX10 low cut spiral achieved low specific gravity cut points in the range of 1.4 to 1.55 depending on the source of material tested. In this work, the SX10 was tested on the South African Coal as well as a Coal sample from North America. Figure 4 shows the partition curve for the SX7 and SX10 spirals on a South African coal.

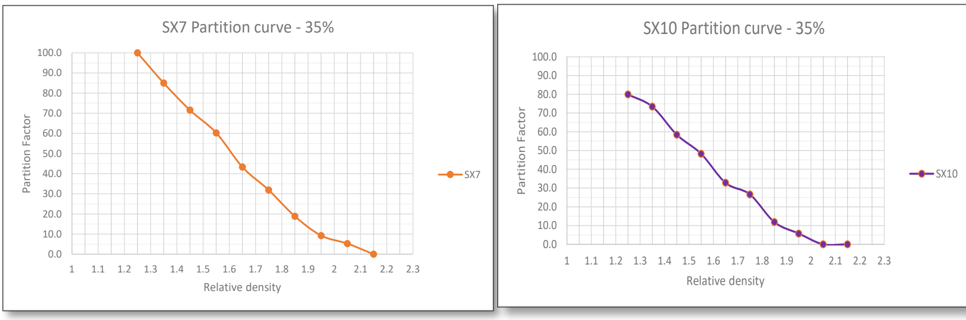

Fig. 5. SX7vs SX10- partition factors [20]

Figure 5 shows a cut point of 1.6 on the SX7 and 1.55 on the SX10 spiral respectively. The cut point is lower for the SX10 spiral, but with more misplacement of product to discard. The mass yields and cut points attained matched the values found by Mathumbu and Ramsaywok [19]. A float sink investigation revealed that both spirals had a product yield of ± 40% and a waste yield of ± 60%. The results are shown in Table 1 below.

Table 1: Testwork Results on South African Material [20]

Feed				Product (fraction F)		
	CV (MJ/kg)	Ash (%)		CV (MJ/kg)	Ash (%)	Mass Yield (%)
SX7	22.45	25.18		24.41	17.87	53.73
SX10	21.88	26.66		26.18	15.50	34.60
MX7	22.36	26.97		27.07	15.00	61.80
MX10	21.74	28.80		26.90	14.10	41.80
SX10	19.76	34.04		27.32	14.30	40.20

Figure 6 shows a partition curve for the SX10 spirals for a North American coal. The samples from each test were combined over the spiral trough profile to create partition curves for the 1 x 0.25 mm (1 mm x 60 mesh) and 0.25 x 0.15 mm (60 mesh x 100 mesh) fractions, as seen in Figures 6. In both studies, low specific gravity cut points in the range of 1.4 to 1.56 were achieved [20].

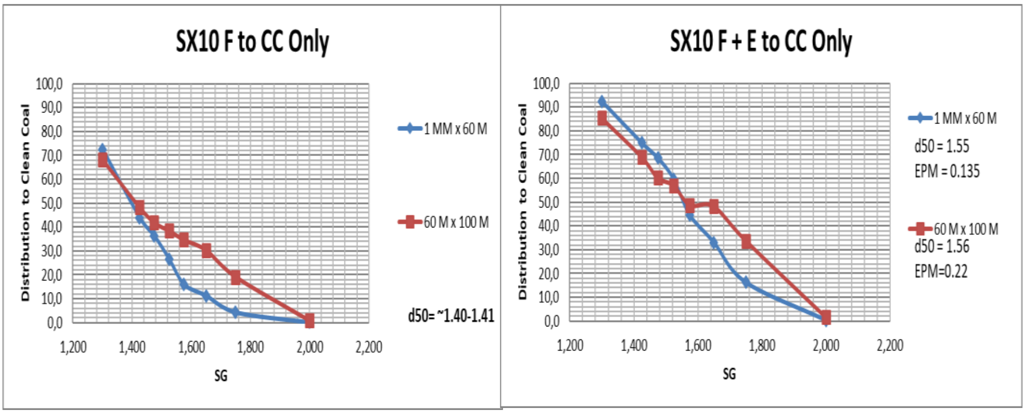

Fig. 6. Partition curve (F only) vs (F+E) 2.2 tph (2.4 stph) and 6.8 m^3/h (30 gpm) [20].

Where F fraction of the mouth organ was considered as the product alone, the cut points for the different size fractions were similar, suggesting that the finer fraction does not significantly impair performance. [20]. The spiral has also demonstrated the ability to handle higher solid concentration and feedrate[3]. Figure 7 shows relationship between throughput and product quality on the SX10 spiral.

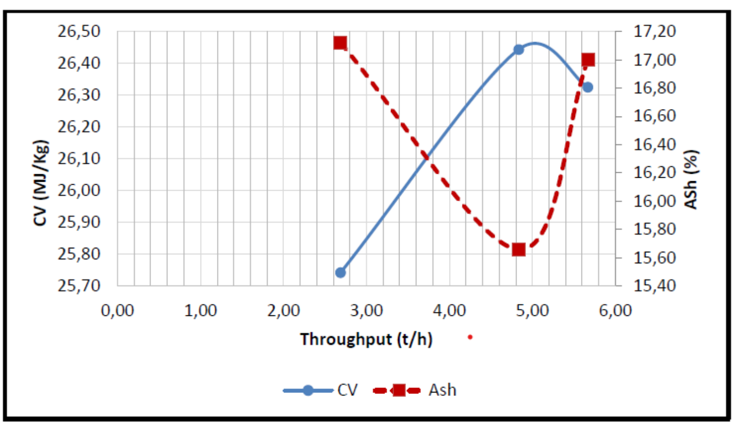

Fig. 7. Relationship between throughput and product quality on the SX10 spiral [3]

Although the spiral can handle higher solid concentration and feedrate it should also be noted that the capability of the spiral to produce low cut or low ash product decreases with an increase in solid concentration and feedrate.

3 Conclusion

Recent advancements in spiral technologies in the past 11 years have led to the introduction of low-cut spirals, such as the LC3 and SX10 spirals. These spirals have been shown to produce SG cut point in the range of 1.4 to 1.55. The developments involved altering spiral profiles, adding splitters and repulpers enabling auto rejection of gangue along the length of the spiral to increasing surface area of separation, increasing number of turns to increase retention time, reduce turbulence to enhance separation and recovery of ultrafine coal.

The LC3 features a distinctive trough design and a detailed gravity profile throughout the particle bed. This design allows for lower cut points due to a variable density profile, resulting in a gentler flow regime. The LC3 is created using dynamic pitches and profiles that adjust for the slurry's shifting characteristics as it travels down the trough. Flatter pitch and additional turns resulted in additional residence time.

The SX10 spiral, a 10 turn, 1000mm diameter spiral by Multotec, is a 3 stage in 1 low-cut spiral with 2 repulpers positioned at the 4th and 7th turns. It is an extension of the SX7 spiral, with an additional repulper and 3 turns increasing retention time. The spiral has 2 offtakes that direct discard into the auto reject center column, allowing more material to be processed without excessive particle crowding. The offtakes are positioned before the repulpers, ensuring a favorable environment for low-cut products.

The future work in spiral development should investigate configurations that can achieve a good compromise between low-cut points, feedrate, and yield. If low-cut is achieved at the expense of yield to the final product, this results in losses of recoverable coal to the final tailing which consequently adds to the environmental liability of the operations and all the consequences related to having a tailings dam. Achieving low cut at reduced capacities means that more spirals would be required than when using the conventional spirals and consequently the footprint of the installation will be increased. Extended height requirements also limit the utilization of a spiral; future designs should provide flexibility for spirals to be retrofitted in existing operations.

References

1. M. Steyn, R.C.A. Minnitt, Thermal coal products in South Africa. J. S. Afr. Inst. Min. Metall. **110**, 593(2010) https://www.scielo.org.za/pdf/jsaimm/v110n10/04.pdf

2. T. England, P.E. Hand, D.C. Michael, L.M. Falcon, A.D. Yell, Coal preparation in South Africa, South African processing society (2002)

3. H.S. Baloyi, M.C. Tjabadi, M.C. Diketane, Development of a high capacity, low cut spiral for the coal industry, in Proceedings of the SACPS- 2019 Conference, Secunda, South Africa, August 19 - 22 (2019)

4. H. C Voges, Tests on the beneficiation of coal fines. J. S. Afr.Inst.Min.Metall. **91**, 41 (1991). https://journals.co.za/doi/pdf/10.10520/AJA0038223X_2014

5. Erasmus, W., Bornman, F., De Korte, J. 2016. Technologies in use for the processing of fine coal, in Proceedings of the XVIII International Coal Preparation Congress- 2016 conference, June 28-July 01, Saint-Petersburg, Russia (2016)

6. M. Asghari, M. Noaparast, S.Z. Shafaie, S. Ghassa, S. Chehreh Chelgani. Recovery of coal particles from a tailing dam for environmental protection and economical beneficiations. Int. J. Coal Sci. Technol. **5,** 253-263 (2018). https://doi.org/10.1007/s40789-018-0197-2

7. P. C Kapur, T.P. Meloy, Spirals observed. Int. J. Miner. Process. **53**,15-28 (1998). https://doi.org/10.1016/S0301-7516(97)00053-7

8. S.K Das, K.M Godiwalla, P. Lopamudra, K.K Bhattacharya, R. Singh, S.P Mehrotra, Mathematical modelling of separation characteristics of a coal-washing spiral, Int. J. Miner. Process. **84**, 118 (2007). https://doi.org/10.1016/j.minpro.2007.05.007

9. P.N Holtham, Primary and secondary fluid velocities on spiral separators. Miner.Eng. **5**,79 (1992). https://doi.org/10.1016/0892-6875(92)90007-V

10. A.B Holland-Batt, The dynamics of sluice and spiral separations. Miner. Eng.**8**, (1995). https://doi.org/10.1016/0892-6875(94)00098-W

11. L. MacNamara, F. Addison, N.J Miles, P. Bethell, P. Davies. The application of new configurations of coal spirals, in Proceedings of the 12th International Coal Preparation Conference and Exhibit, Lexington, Kentucky, May 2-4, 43 (1995)

12. D.G Osborne, Fine coal cleaning by gravity methods: a review of current practice. Coal Preparation, 2, 207(1986). https://doi.org/10.1080/07349348508905166

13. T.R., Prinsloo, R. L Abela, Multiple Stage Fine Coal Spiral Concentrators. In Proceedings of the International Coal Preparation Congress, Brisbane, October 4-10 (1998)

14. C.M. Ramotsabi, W. Erasmus, F. Bornman, The effect of repulping on the SX7 spiral, in Proceedings of the International Coal Preparation Conference-2015 conference, Lexington, Kentucky, April 27-29 (2015).

15. C.M Ramotsabi; H.S. Baloyi, R. Ceko, F.F. van de Venter, Low cut SX10 spiral and Optima classifier combination: Optimizing a fine coal processing, in Proceedings of the SACPS- 2021 Conference, October 12-14 (2021).

16. M.K., Palmer, The Development of a New Low Cut-Point Spiral for Fine Coal Processing, in Proceedings of the International Coal Preparation Congress, June 28-July 01, Saint-Petersburg, Russia (2016)

17. M.K. Palmer, W.S Weldon, A new low cut-point spiral for fine coal separation, in Proceedings of USA Coal Preparation Conference (2013)

18. A De Andrade, C Thornton, D. MacHunter, J. Agenbag. Advances in spiral automation and ultrafine processing (2017)

19. P. Ramsaywok, P. Mathumbu, A straight up single pass comparison of a low-cut spiral and a conventional spiral in the South African coal industry, in Proceedings of the Southern African Coal Processing Society- 2017 conference, Coal Processing – the key to profitability (2017)

20. B. Arnold, P. Bethel, W. Erasmus, F Bornman. Development of a Low Specific Gravity Cut Point Spiral, in Proceedings of Coal Preparation Society of America- 2018 conference, Lexington, Kentucky (2018)