COALTECH 2020

Task 4.11.1 (a)
De-Sliming of Fine Coal

BY

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TABLE OF CONTENTS

List of Tables

List of Figures

1. Introduction

It is standard practice in coal processing plants to de-slime the feed to fine coal processes such as spirals, Teetered Bed Separators (TBS) and dense medium cyclones. During the de-sliming process, the ultra-fine (minus 100 micron) size fraction is removed from the bulk minus 1 mm coal and the plus 100 micron size fraction is sent for processing in the spirals or other equipment. Although 100 micron is used to define ultra-fine coal here, the actual size used in industry can vary between about 100 and 200 microns.

At present, hydro-cyclones are used almost exclusively to carry out the de-sliming. Since cyclones are not 100% efficient, some ultra-fine coal is still contained in the spiral (or other unit) feed and much of these ultra-fines report to the spiral product.

The ultra-fine coal usually has high ash content and downgrades the spiral product as a result. Table 1 below shows the size and ash content distribution for a typical spiral product.

Table 1: Spiral product size and ash distribution

Screen size (micron)				% Fractional	% Cumulative	Ash % Fractional	Ash % Cumulative
		+	1000	0.5	0.5	10.4	10.4
-	1000	+	500	19.1	19.5	10.5	10.5
-	500	+	250	26.7	46.2	11.3	11.0
-	250	+	150	10.4	56.6	11.9	11.1
-	150	+	106	14.0	70.6	15.3	12.0
-	106	+	90	5.1	75.7	21.9	12.6
-	90	+	75	4.8	80.6	25.1	13.4
-	75	+	45	4.8	85.4	38.3	14.8
-	45	+	25	5.1	90.5	40.2	16.2
-	25	+	0	9.5	100.0	44.2	18.9

The product shown in Table 1 contains 29,3% of minus-106 micron material. If this material could be removed from the product, the ash content would be reduced from 18,9% to 12,0%. The advantages from a product quality control point of view are obvious.

In the case of dense-medium beneficiation of the minus 1 mm size fraction it becomes even more important to remove the ultra-fine coal prior to processing since it is generally accepted that the ultra-fine coal will lower the recovery efficiency of the magnetic separators used to recover the magnetite medium. As in the case of spirals, the final product will also be degraded by the presence of ultra-fine coal.

The presence of ultra-fine coal particles in the spiral, TBS or cyclone product results in higher final product moistures since the high surface area of the ultra-fine particles negatively influences the dewatering of the product.
Various techniques have been employed or investigated to effectively de-slime coal at 100 microns but the ideal method still does not exist.

This report contains an overview of a number of de-sliming techniques.

2. Performance measures used for size classification equipment

The performance of size classification equipment is best described by the partition curve, a graphical depiction of the probability of a particle reporting to the oversize (coarse) size fraction.

The curve, shown in Figure 1, is characterised by the following parameters:

- The curve is S-shaped and approaches a probability of 1,0 at large particle sizes, provided there is no by-pass of the coarse material to the undersize flow-stream

- The slope (α) of the middle part of the curve reflects the sharpness of separation with a steeper curve being indicative of a sharper separation. The slope is usually reported as the 'Imperfection' of the separation. Imperfection is defined as:

$$\text{Imperfection} = \frac{(S_{75} - S_{25})}{2} \qquad (1)$$

  Where S_{75} = the screen size at 75% recovery to oversize and
  S_{25} = the screen size at 25% recovery to oversize

- The amount of water reporting (short-circuiting) to the oversize flow-stream is indicated by the value of Rf. Some ultra-fine particles are transported to the coarse product stream by this flow of water and causes the curve to exhibit a 'tail' towards the finest size ranges

- A size at which a particle has an even probability of reporting to either the oversize or the undersize flow-stream. This size is referred to as the cut-size (d_{50})

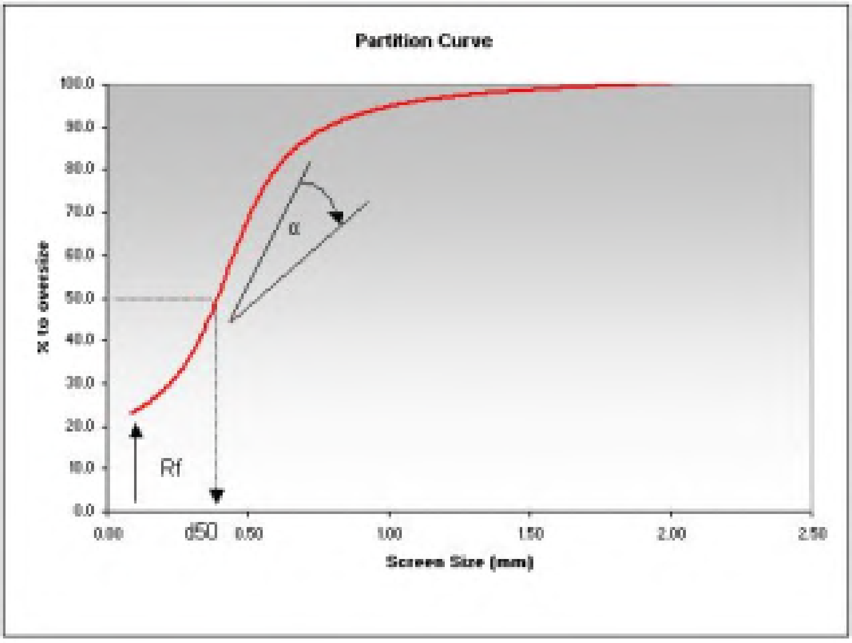

Figure 1: Partition Curve

In addition to the size classification performance of de-sliming equipment, other factors such as throughput capacity, ease of use and maintenance as well as the capital and operating costs need to be considered.

3. Hydro cyclones

Hydro cyclones are at present the preferred de-sliming method used in South Africa. These units are relatively inexpensive, have very high capacity and are easy to operate and maintain. The de-sliming cyclones installed in the Coaltech pilot plant are shown in Figure 2.

Figure 2: De-sliming cyclones

Unfortunately, cyclones do not provide for the most effective de-sliming of the feed to fine coal beneficiation plants, mainly as a result of the so-called ‘short circuiting’ of ultra-fine coal to the underflow stream. The amount of ultra-fine coal that reports to the underflow is proportional to the water split. Another very important consideration, especially in the case of coal, is the fact that the feed to the hydro cyclones is not homogeneous and contains a wide range of particle densities.

A hydro-cyclone separates materials based not only on size but also according to the relative density of the material. If, for example, a cyclone classifies coal at 100 microns, shale will be classified at about 40 microns and pyrite will be classified at approximately 20 microns. The fine shale and pyrite will both report to the cyclone underflow. The implication of this is that the cyclone underflow, the ‘de-slimed’ product, contains, other than the short-circuited ultra-fines, also fine high-density material. Some material, coarser than 100 micron, will also erroneously report to the cyclone overflow. This is usually coal of the lowest density - which also happens to have the best quality.

The performance of hydro cyclones is dependent on a number of factors such as the percentage of solids in the feed, feed pressure, cyclone configuration etc. The sizes and types of hydro cyclones used in the coal industry vary but cyclones of about 350 mm diameter seem to dominate. The performance of a typical 350 mm de-sliming cyclone is shown in Table 2 below.

Table 2: Typical hydro cyclone performance

Screen Size (micron)	% Weight		% of Feed		Calc. Feed	Mean Size	Part. Number
	U/F	O/F	U/F	O/F			
+ 2000	0.31	0.00	0.16	0.00	0.16	2000.0	100.0
- 2000 + 1000	1.39	0.00	0.72	0.00	0.72	1500.0	100.0
- 1000 + 500	17.87	0.00	9.27	0.00	9.27	750.0	100.0
- 500 + 250	33.42	1.54	17.34	0.74	18.08	375.0	95.9
- 250 + 106	24.74	14.75	12.83	7.09	19.93	178.0	64.4
- 106 + 75	5.68	4.74	2.95	2.28	5.23	90.5	56.4
- 75 + 45	3.75	14.98	1.95	7.21	9.16	60.0	21.3
- 45 + 25	3.81	7.67	1.98	3.69	5.67	35.0	34.9
- 25 + 0	9.04	56.33	4.69	27.10	31.79	12.5	14.8
Whole Coal	100.00	100.00	51.89	48.11	100.00		

The partition curve derived from the data in Table 2 is shown in Figure 3. The performance parameters for the curve are d_{50} = 99,4 micron and Imperfection = 0,073.

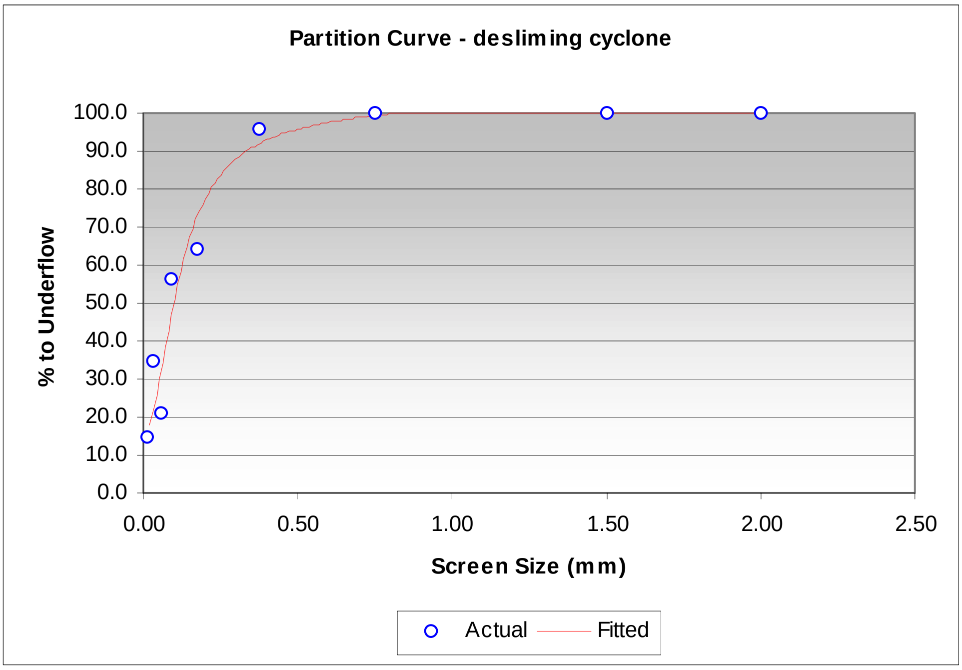

Figure 3: Partition curve for de-sliming cyclone

Numerous attempts have been made to improve the performance of hydro cyclones. These include alternative cyclone designs and using more than one cyclone in series. Another method tried, is the use of water injected into the apex of the cyclone to remove the ultra-fine coal contained in the water leaving the cyclone via the spigot.

Mohanty[1] tested the performance of a 'Cyclowash' (a Krebs cyclone with water injection into the apex) and found that the short-circuiting of ultra-fine coal to the underflow could be almost completely eliminated. It was also reported that the injection of large amounts of elutriation water into the cyclone apex increased the separation size.

Firth et al[2] investigated a number of different de-sliming techniques and came to the conclusion that a circuit consisting of three hydro cyclones, arranged in a rougher, cleaner and scavenger configuration, is the most efficient and economical means to de-slime fine coal. Figure 4 below shows the arrangement of cyclones in such a circuit.

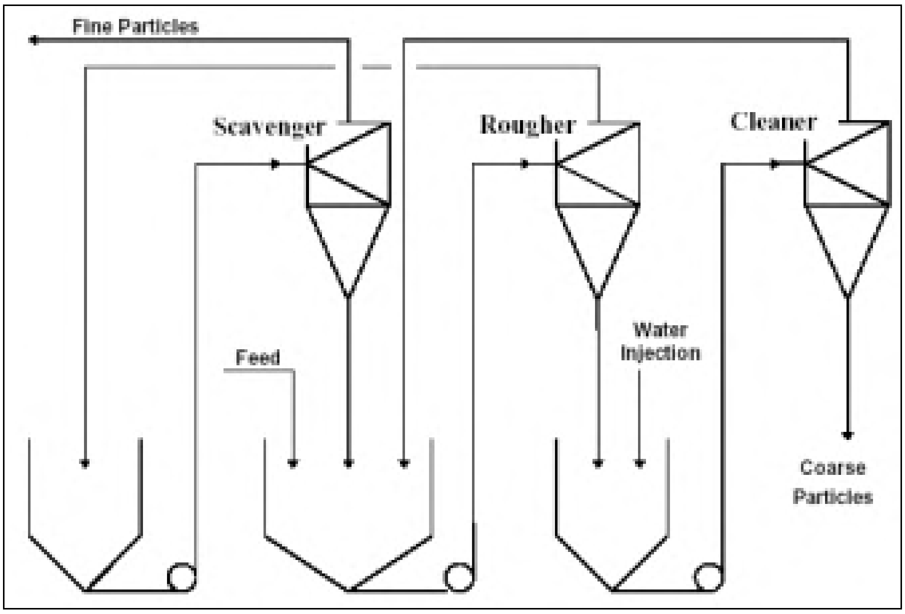

Figure 4: Arrangement of cyclones in three-stage counter current circuit

Based on these findings, a pilot circuit was constructed and tested at Moura Colliery in Australia. The test plant at Moura is shown in Figure 5.

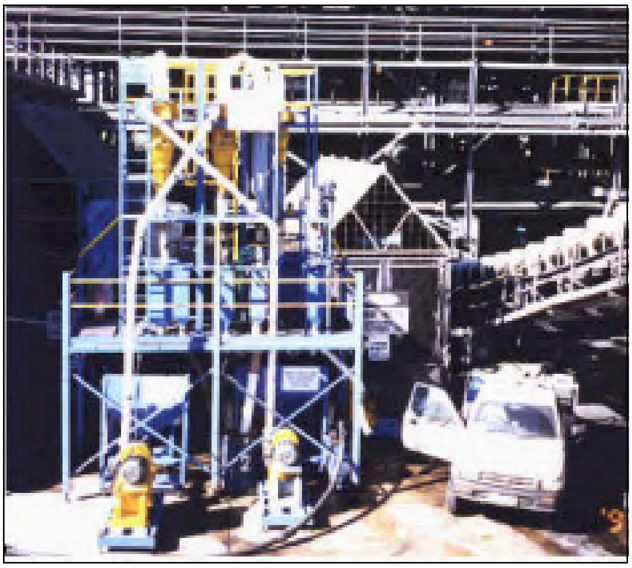

Figure 5: Three-stage cyclone test plant at Moura

The results obtained from the tests conducted at Moura showed that a 50 percent reduction of short-circuited ultra-fines in the cyclone underflow is possible with the three-stage cyclone circuit. The amount of misplaced coarse coal in the cyclone overflow was also significantly reduced.

It is possible, if sufficient height is available in a plant, to use only one pump to feed the three-stage cyclone plant. This is illustrated in Figure 6.

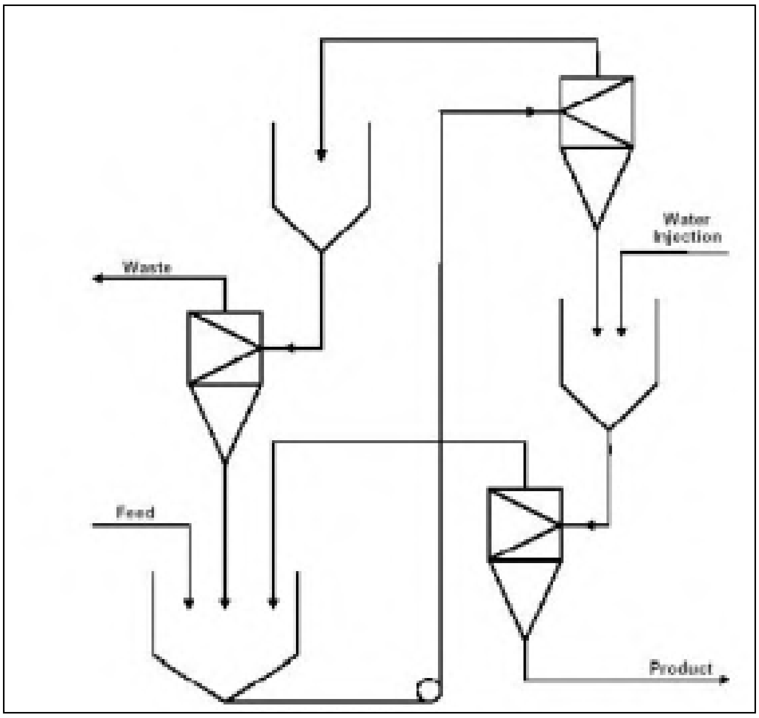

Figure 6: Arrangement to feed 3 cyclones with a single pump

In theory, a smaller diameter cyclone will result in a smaller cut-point size. Since the cyclone overflow stream normally contains ultra-fine coal that is disposed of, a fine cut-point size implies minimum loss of coal. For this reason, banks of 250mm or 350mm cyclones are usually installed in South African plants to de-slime the feed to spiral plants. Unfortunately, small diameter cyclones have small diameter spigots and problems of roping or blockage are often experienced in practice.

In practice, a large diameter cyclone, operating normally without overloading of the spigot, made possible by the fact that the spigot has a large diameter, has a much smaller cut-point size than a small, roping cyclone. It is also much easier to operate one or two large cyclones than a large bank of small ones. Although the concept of replacing a bank of small cyclones with one large (610mm) cyclone is not new as demonstrated by Figure 7 below, some work in this regard has recently been carried out, both locally[7] and in Australia by O'Brien et al[5]. Positive results were reported in both cases.

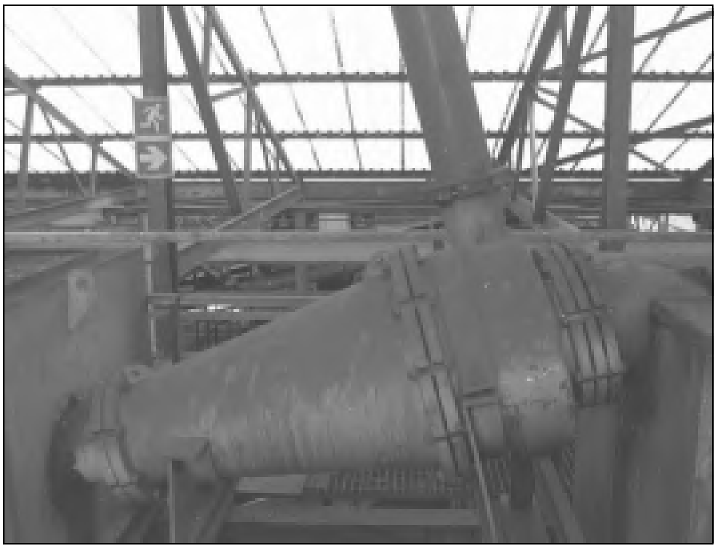

Figure 7: Large diameter de-sliming cyclone (Landau 3 – 1987)

4. Delkor Fast screen

The Delkor Fast Screen (DFS) was initially chosen as the de-sliming device in the Coaltech 2020 fine coal dense medium test plant. This decision was based on the successful application of the DFS in other industries, especially in the gold industry. A full-scale DFS was also installed and operating at Optimum Colliery at the time.

The DFS, shown in Figure 8, consists of a continuous woven screen cloth running on rollers. Slurry is fed onto the screen cloth and material finer than the screen apertures is transported through the screen cloth by the action of the water draining through the apertures. Water sprays are employed to wash the screen cloth continually, thus preventing it from blinding.

Figure 8: Delkor Fast Screen

The DFS installed in the Coaltech plant was found to work well at low feed rates but the screen could only handle approximately 50% of the required throughput capacity. The following table summarises the result of a test conducted on the DFS installed in the Coaltech plant.

Table 3: DFS performance in Coaltech plant

Screen size (micron)	% in DFS feed	% in DFS product
+500	20,2	33,5
+212	36,5	38,5
+150	9,4	8,3
+106	5,3	4,9
-106	28,6	14,8

The DFS in the Coaltech plant has now been replaced by two 350mm diameter hydro-cyclones. The screen at Optimum was found to de-slime very effectively but proved difficult and expensive to maintain and has since been removed from the circuit.

5. Kroosh – The ‘ultimate’ screener

Kroosh Technologies developed a multi-frequency adapter, the “Kroosher®”, to improve the throughput capacity and the efficiency of screening, especially at small aperture sizes. The Kroosher is a purely mechanical device containing elastic elements. The unit is bolted onto a conventional vibratory screen. Figure 9 shows the Kroosh screen and the placement of the Kroosher units.

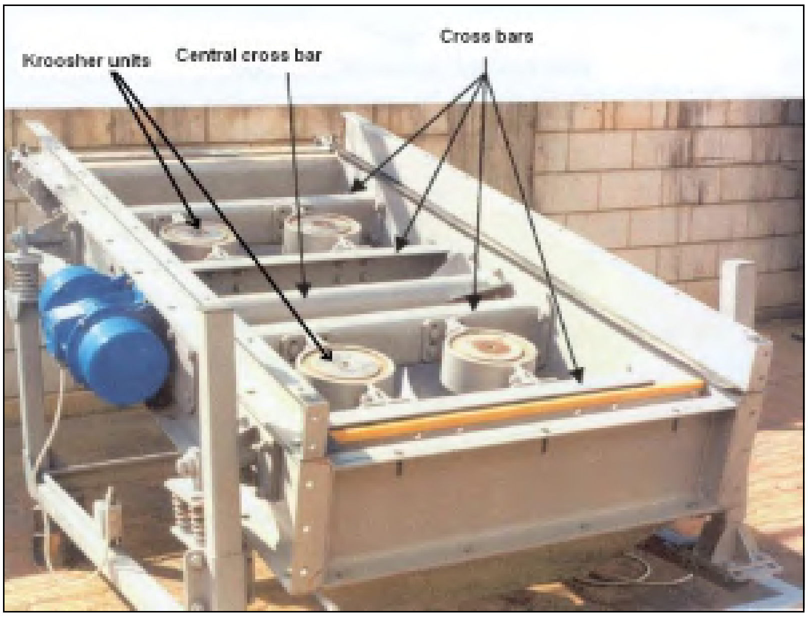

Figure 9: Kroosh screen

The Kroosher uses the single-frequency vibrations generated by the motor-vibrators of the screen to generate multi-frequency non-harmonic high-energy vibrations that are then transmitted to the screening surface, thus improving the screening process.

The Kroosher units are bolted to the screen cross bars with mounting units. The single-frequency vibrations, generated by the vibrator motor, are transmitted to the Kroosher units through the screen's cross bars and through the mounting brackets.

The Kroosher units convert the single-frequency vibrations into multi-frequency vibration and amplify the vibrations between 300 and 500 times. The amplified, multi-frequency vibrations are then transmitted to the 'beaters' or 'hitting pads' assembly attached to the inner element of the Kroosher unit.

This arrangement can be seen in Figure 10 below.

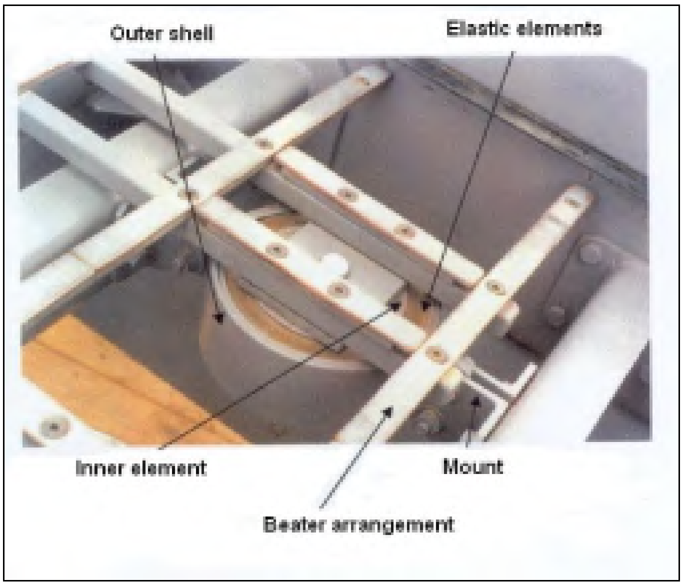

Figure 10: View of Kroosher unit

The 'working' screen cloth with apertures of 100 micron is supported on a stretched support cloth with 2 mm apertures. The vibrations generated by the Kroosher units are transferred to the support screen through the 'beater' assembly.

In order to assess the performance of the Kroosh technology, a 2 m x 1 m screen, fitted with four Kroosher units, was purchased and installed at Optimum Colliery as part of a Coaltech 2020 project. Optimum Colliery offered to share the cost of the installation with CoalTech 2020 and to host the test work. A Kroosh screen was also purchased and installed by Anglo Coal at Goedehoop. Following the completion of the tests at Optimum, the Kroosh screen was installed at Navigation Plant and further tests were conducted.

The following graph, Figure 11, shows the results obtained during one of the tests conducted at Navigation. The performance parameters for the graph shown in Figure 12 are d_{50} = 119 micron and Imperfection = 0,049.

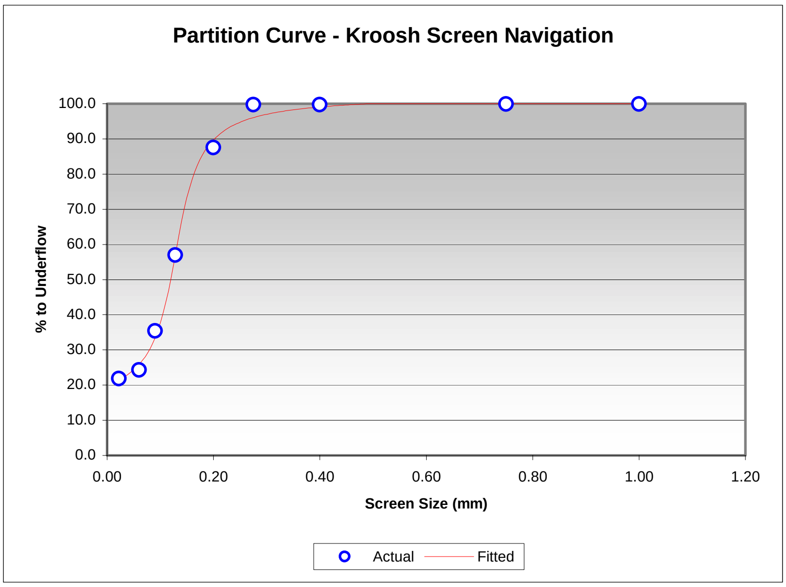

Figure 11: Partition curve for Kroosh Screen at Navigation

The following graph (Figure 12) shows a comparison between the separation obtained on the Kroosh screen and that obtained from a hydro-cyclone. As can be seen from the graph, a sharper separation is obtained from the Kroosh screen.

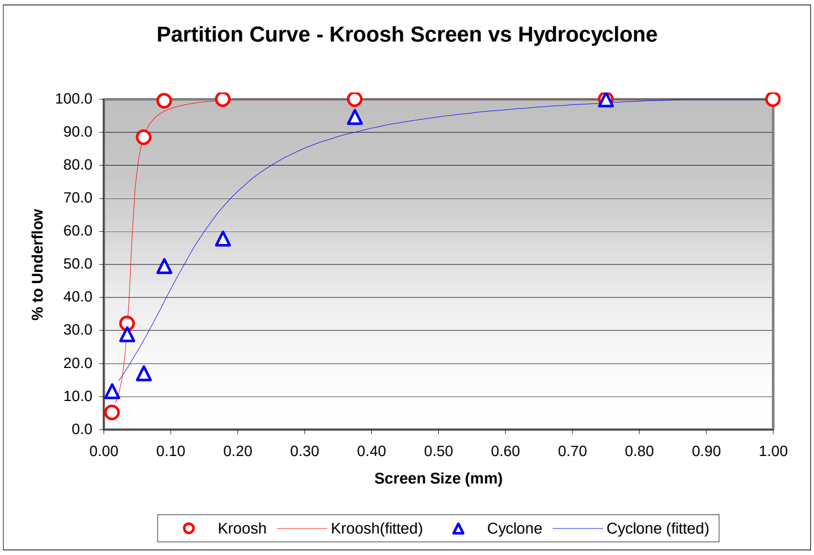

Figure 12: Comparative partition curves

The conclusions drawn from the test work conducted on the Kroosh screen were that the Kroosh screen is able to screen very efficiently at small aperture sizes but the screen does not have the required throughput capacity. The mechanical reliability of the screen also remains unproven.

6. Sieve bend

The sieve bend was originally developed by DSM (Dutch State Mines) to provide a method of size separation at small particle sizes – this was difficult to achieve with conventional screens.

A sieve bend is an inclined, curved, wedge wire screen with the slot openings of the screen arranged perpendicular to the direction of flow of slurry. As slurry flows over the sieve bend, thin layers of the fluid are ‘shaved’ from the slurry by the openings in the screen surface. The fine particles contained in the slurry are carried by the flow passing through the screen apertures and are thus removed from the main slurry stream. The operating principle of a sieve bend is illustrated in Figure 13 below. A photograph of a sieve bend in operation is shown in Figure 14.

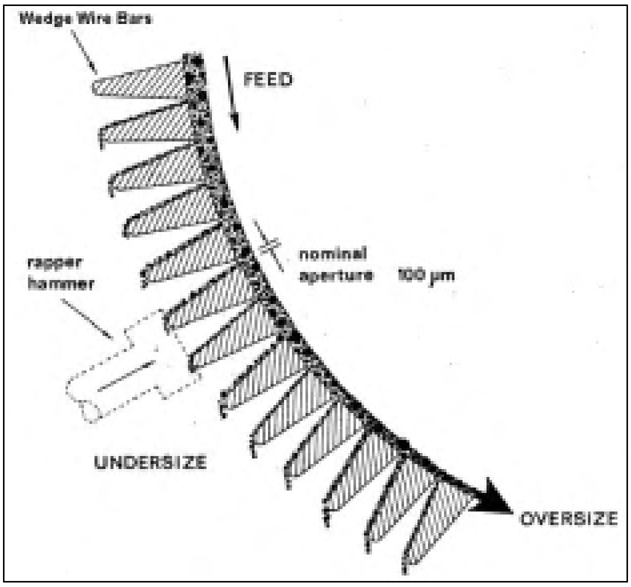

Figure 13: Sieve bend

Figure 14: Sieve bend in operation

The 'projected' screen aperture, by virtue of the design of the sieve bend, is approximately 50% of the actual width of the slots. Sieve bends therefore have a cut-point equal to about half the actual screen slot apertures.

During use, the leading edges of the screen surface are worn due to abrasion whilst the trailing edges are sharpened. It is therefore necessary to rotate the screen surface regularly to ensure continued efficient screening.

Vibration or 'rapping' of the screen surface is sometimes employed to ensure that the screen apertures do not become blocked by near-size particles.

The slurry capacity of sieve bends is dependent on the width of the screen surface and the aperture size of the screen slot openings.

The efficiency of screening is dependent on the aperture size of the screen, the solids content of the slurry and also on the flow rate of slurry across the sieve bend. There is an optimum volumetric flow-rate at which the efficiency is at a maximum. Table 4 below show the relative volumetric optimal flow rates for a number of different screen aperture sizes as determined by Firth et al[2].

Table 4: Capacity of sieve bends[2]

Screen apertures (mm)	Capacity for maximum efficiency (m3/hr/m)
0.12	29.9
0.25	57.6
0.30	72.0
0.50	122.4
1.80	198.0
3.50	370.8

A partition curve based on published data[3] for a sieve bend is shown in Figure 15. The performance parameters for the curve are d_{50} = 132 micron and Imperfection = 0,047.

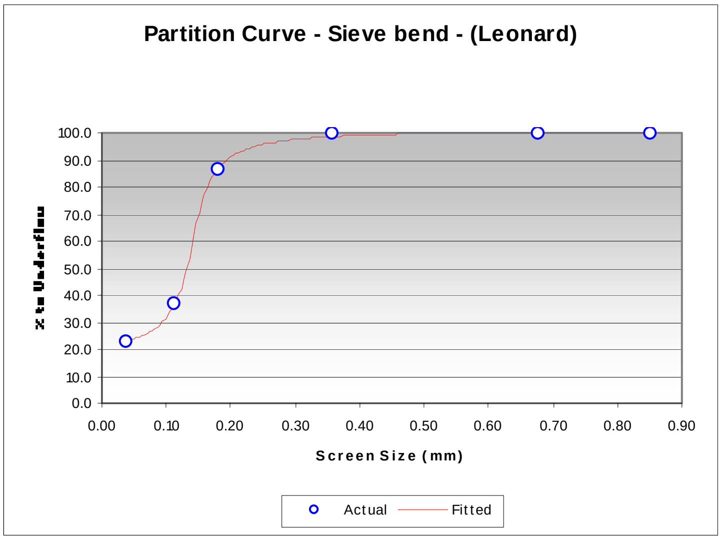

Figure 15: Partition curve for sieve bend

The volumetric flow rate of feed to a sieve bend is a critical parameter and has a large influence on the efficiency of the size separation affected by the sieve bend. Ideally, the flow of slurry should terminate at the end of the sieve bend and only the oversize material should be discharged over the lip of the screen surface. This would imply that all the fine material has been removed through the sieve and only the oversize material remains on top of the screen surface. If, however, there is a strong flow of slurry over the end of the screening surface, fine material will be carried over into the oversize product and hence the Rf-value will increase.

7. Pansep Screen

The Pansep screen was developed in South Africa by Particle Separation Systems (PSS) in the late 1990s to incorporate a system of separate non-flexing screen cloths each tensioned within their own frame and linked together as a series of segmented pans. The essential advantage was that the screen cloth effectively could be any type appropriate to the duty required, without consideration of a need for flexibility or resilience to fatigue. The screen selection is therefore governed by the separation characteristics required, including open area ratio, accuracy and shape of apertures.

A consequent benefit was the facility to use the return pans for screening operations, by using the reverse side after an intermediate wash. This effectively doubles the capacities for a given screen size

The operating principle of the Pansep screen is shown in Figure 16.

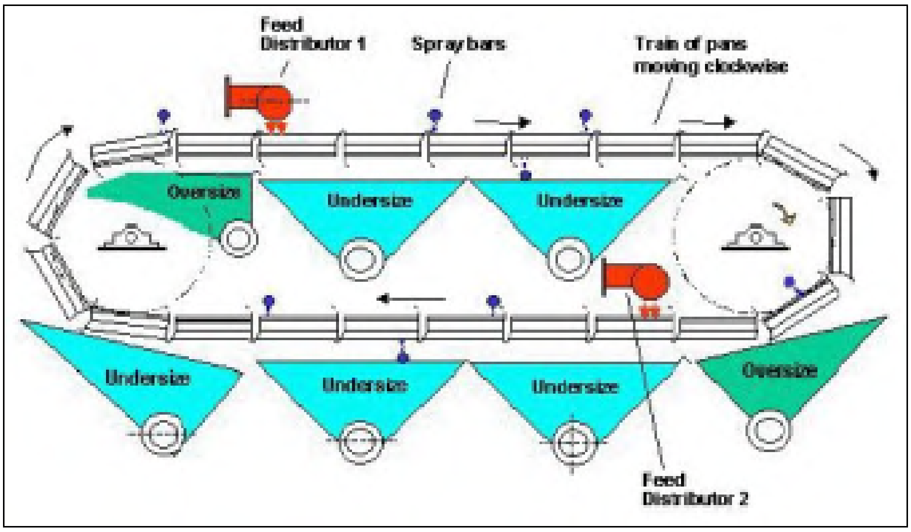

Figure 16: Pansep screen

The first commercial application of the Pansep screen system was in 1998 at Optimum Colliery where the unit was employed to remove minus 200-micron ultra-fines from the spiral product prior to centrifuge dewatering of the product. This provided an upgrade from about 19% ash to less than 12% ash.

Two $4m^2$ Pansep screens operating at 14m/min were initially installed to treat 56 t/h, with 39% fines removed at an oversize recovery (screen efficiency) of 94%.

Subsequently two further units, each $9m^2$ were later installed at Optimum. The Pansep screens at Optimum are shown in Figure 17.

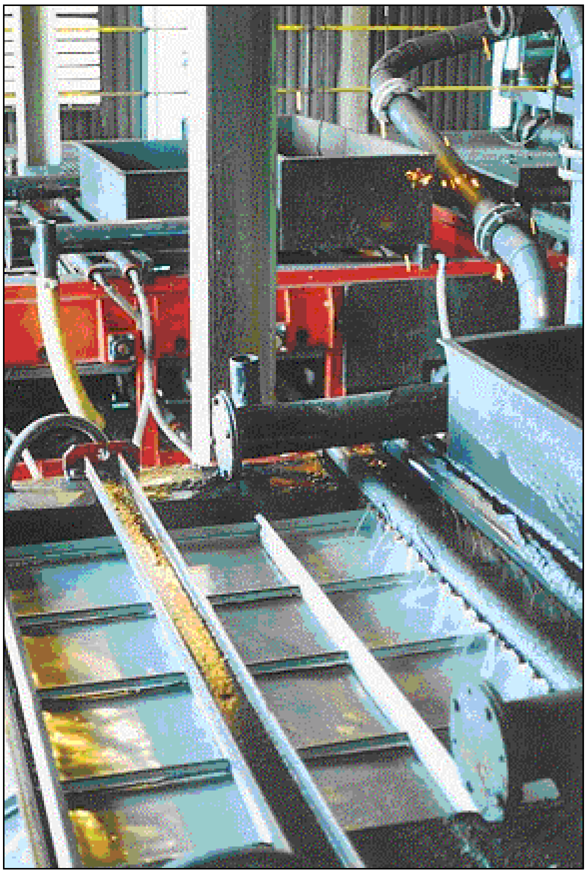

Figure 17: Pansep screens at Optimum

A partition curve, based on published[6] data for the Pansep, is shown in Figure 18. The performance parameters are d_{50} = 181 micron and Imperfection = 0,049.

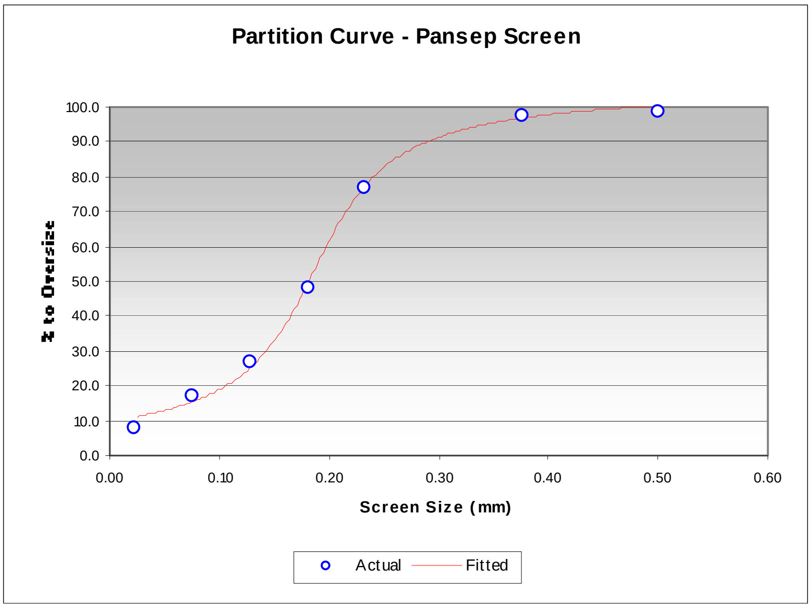

Figure 18: Partition curve for Pansep screen

Mohanty[1] carried out extensive testing of the Pansep screen, in comparison to other de-sliming equipment and concluded that the Pansep was very efficient in the removal of ultra-fines from a fine coal feed.

Unfortunately the Pansep proved to be very maintenance-intensive and the units at Optimum are no longer in use, despite the very good screening performance obtained.

8. Derrick screen

In 1973 Derrick Manufacturing introduced high-frequency screening machinery into the coal industry in the US.

The first design consisted of a 4 ft by 8 ft single deck screen frame with three 100 mesh (150 micron) woven wire screen surfaces divided by troughs for the addition of wash water. The machine was equipped with a special high-speed, low amplitude vibrator.

The first application involved the recovery of saleable +150 micron fine coal from a plant effluent stream containing minus-600 micron solids that were contaminated with high ash slimes.

It was found that excessive blinding of the 100 mesh screen surfaces occurred during operation. The screen required frequent brushing and washing to maintain product quality.

A new layered or "sandwich screen" surface was developed by Derrick to overcome these problems. The sandwich screen consists of two independent fine, square, woven wire screens held together in a common binding in such a manner as to allow cross wires of the bottom surface to create an interference in the free openings of the top screen. This is illustrated in Figure 19.

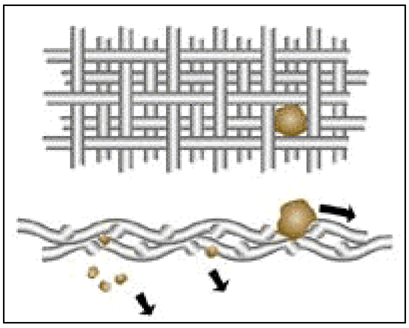

Figure 19: Derrick “Sandwich’ screen

By adhering to correct opening vs. wire diameter ratios, the blinding of near-size-oversize particles experienced with conventional fixed opening woven wire may be prevented. Product separation is thus achieved when fine particles pass through a nominal opening created by cross wires from both fine screen surfaces.

It was reported[2], from a study conducted, that the performance of the Derrick screen was dependent on the screen aperture size, the flow rate of solids and the solids content of the feed slurry. For relatively low feed rates an acceptable classification was obtained but the separation deteriorated with smaller apertures, higher flow rates and higher solids contents. The by-pass of ultra-fine particles increased significantly under the latter conditions.

The same trends were observed during tests conducted at Optimum and Navigation with the Kroosh screen. The problem seems to stem from the fact that effective screening only occurs as long as there is no formation of a bed on the screen surface. As soon as a bed has formed, the ultra-fine particles become trapped in the bed and are discharged with the oversize material. The effective operation of the screen then becomes one of dewatering rather than size classification.

Under conditions of low feed rate and low solids content, the formation of a bed is minimised and hence more effective screening occurs. However, this is only possible at low throughput rates.

Since the classification operation occurs rapidly, over a short section of the screening surface, followed by bed formation, indications are that screens used for classifying by size should be short in length.

Derrick realised this and developed a multi-feed screen to maximise size classification. The machine has three independent screening sections within a single live frame. A three-way flow divider mounted on a supporting tower above the live frame body feeds the machine.

The device is constructed to provide uniform feed streams to distribution boxes located at the head of each screen section. A single high-speed vibrator is mounted in the centre of the live frame. It aids sizing by rapidly breaking fluid surface tension at the screen surface and conveying oversize solids away from the oncoming load.

A diagram of the multi-feed system is shown in Figure 20.

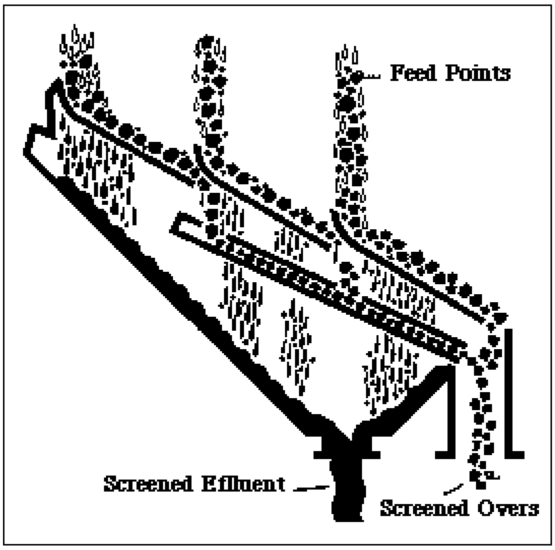

Figure 20: Derrick Multi-feed screen

The same conclusion was reached during tests conducted with the Kroosh screen and it was found that 2 feed points gave better results, for the same feed rate, than a single feed point. Figure 21 below shows the reported[4] performance for a Derrick screen. The performance parameters for the curve are d_{50} = 141 micron and Imp = 0,043.

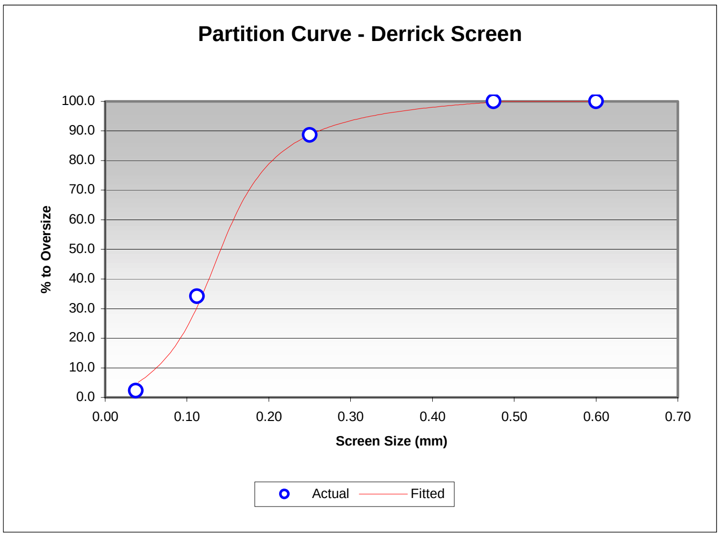

Figure 21: Partition curve for Derrick screen

9. Conclusions

When comparing the separation efficiency of the different types of available de-sliming equipment, it is clear that no single available method is perfect.

The difference between the separation mechanisms of hydro-cyclones and screens is the fact that the separation affected by a cyclone is based on both the particle size as well as the density of the particles. In screening, particle size is the only criterion. The fact that screens offer a 'clean' cut at a specific size is an important consideration.

It would unfortunately seem that, based on experience with various types of screens tested in South Africa, they are all difficult and expensive to operate and maintain. In addition, screening is only effective at low throughput rates. In order to achieve efficient screening on a production scale, a large number of screens will be required.

Sieve bends, operating under the right conditions, screen almost as effectively as the more complicated vibrating types of screens and offer reasonable capacity at moderate cost.

Cyclones, despite the fact that fine high-density material is misplaced to the de-slimed product, offer large throughput capacity and simple operation at reasonable cost.

Table 5 below summarises the performance characteristics as well as the relative throughput and cost of the various types of de-sliming equipment. An overall rating of 'A' implies that a particular unit is well suited to South African plants whilst a 'B' rating implies that a unit may be not suited or still unproven.

Table 5: Summary of de-sliming equipment

Equipment type	Typical Imperfection	Capacity	Relative Cost	Overall rating
Hydro Cyclones	0,073	High	Low	A
Delkor Fast Screen	Not available	Low	High	B
Kroosh Screen	0,049	Low	High	B
Sieve Bend	0,047	High	Low	A
Pansep Screen	0,049	Low	High	B
Derrick Screen	0,043	Low	High	B

10. Recommendations

The simplicity, low cost and high throughput capacity of hydro-cyclones make them the de-sliming method of choice in South Africa. This is unlikely to change in the short term.

It would be advantageous to investigate the use of the three-cyclone circuit for application in special circumstances.

The use of cyclone / sieve bend combinations could provide a simple solution in cases where it is essential to not only de-slime but also to remove the fine high-density material.

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