Dual energy X-ray transmission sorting of coal

by L. von Ketelhodt* and C. Bergmann†

Synopsis

Dual energy X-ray transmission (DE-XRT) sorting is a recent development in the range of sensor-based sorting technologies available today. DE-XRT is particularly suitable for dry coarse coal beneficiation in the size range -120 mm +12 mm. In this paper, we describe the technology and show the results of a number of test runs conducted on different types of coal from the USA and South Africa. The results have shown that DE-XRT is an effective technology not only for deshaling of coal and removing pyritic sulphur but also for separating coal and torbanite. The use of dry deshaling methods will be more important as water availability becomes a greater concern. DE-XRT is one such technology which will be incorporated in future dry coal processing plants.

Introduction

Most coal beneficiation plants around the world make use of water intense separation processes such as dense medium separator (DMS) or jigging plants. In recent years, dry coal separation technologies have gained interest in the industry for the following reasons:

- Water is rapidly becoming a scarce resource, resulting in increasing costs
- Dry coal has higher heating value than wet coal
- Transportation of moist/wet coal is more expensive than transporting dry coal
- Costly environmental rehabilitation costs of coal slimes
- New coal mines in arid regions are being developed e.g. Waterberg coalfield in South Africa.

Different dry deshaling technologies have been developed and tested on various coal types around the world. These include:

- Air jigs, which are suitable for density separations greater than 1.85 RD in the particle size range of -50 mm +6 mm.[1,2]
- Dry magnetic separators for fine coal -6 mm.[1]
- FGX Separators (air tables) suitable for deshaling -25 mm +6 mm size range.[2]
- Accelerator technology, which is a selective breakage technology reducing 250 mm run-of-mine to a more uniform -25 mm coal.[2]

A new coal beneficiation process is the DE-XRT sorting technology. During 2002–2004, transmission theory and experiments carried out at Delft University illustrated the potential of dual-energy X-ray transmission imaging for the on-line determination of ash content and size distribution of bituminous coal. (Jong, Houwelingen, Kuilman, 2004; Jong, 2002)[9]

Sensor based sorting technology

Ore sorting itself is not a new concept, with hand sorting being one of the first methods of minerals processing. Electronic ore sorting equipment was first produced in the late 1940s.[5] Although still a relatively small industry, ore sorting equipment can be applied to a variety of different applications. 'Ore sorting involves the appraisal of individual particles and the rejection of those particles that do not warrant further treatment'.[5] Salter and Wyatt (1991)[6] discuss that the sorting process can be divided into four interactive sub-processes

- Particle presentation
- Particle examination
- Data analysis
- Particle separation.

Feed preparation is more critical for sorters due the importance of surface characteristics and physical size of the particles; most sorters need a 3:1 or 2:1 ratio between the largest and

* CommodasUltrasort (Pty) Ltd, South Africa.

† Mintek, South Africa.

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smallest particle to be efficient. Once the particles have been properly prepared for sorting they must be presented to the sensor. To operate efficiently the sensor must be able to analyse each single particle. As a result, feed rate and the materials handling methods are the critical components, with this most commonly being done by a conveyor belt or chute.[7]

The critical stage of examining the particle and determining whether material is valuable or barren, is done by a combination of sensor and processing unit. Once the decision has been made as to accept or reject a given particle, a mechanical device is required to physically sort. High pressure jets of air or water and mechanical arms or paddles are generally used to make this separation. Of all the components in a sorter, it is the choice of sensor that controls the design of a sorter.[8]

A multitude of different sensors is available and the choice is generally driven by the mineralogy of a given ore. Optical sensors are the most common sensor type, and has been very successfully used in the industrial minerals industry.[7]

DE-XRT sensor theory[9]

The X-ray transmission scanning method is widely used for baggage inspection at airports. Commodas/UltraSort has drawn upon this basic principle and has developed a sensor system suitably adapted to sorting techniques.

The broad-band X-ray radiation of an electrical X-ray source is applied to the sorter feed material which is moved through the scanning area at a rate of 3 m/s (see Figure 2). The X-ray sensor system, which works like a line-scan camera, registers the X-rays penetrating the material and converts them into digital image data. The sensor system consists of two channels (see Figure 3), each capturing the image of the material in different X-ray energy levels. Each particle attenuates the X-ray radiation received, thus decreasing the modulation amplitude of the sensor to varying degrees, so that these images areas appear in different shades of grey.

The attenuation depends on both the thickness and atomic density of the material. Images of different atomic densities are transformed into images of different spectral ranges, which make it possible to classify different colour pixels according to specific atomic densities. This is accomplished almost regardless of the thickness of the material.

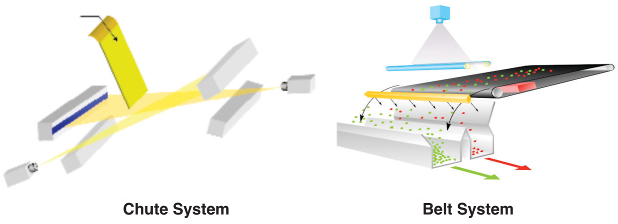


Figure 1—Two types of sorting systems: chute vs. belt.[9]

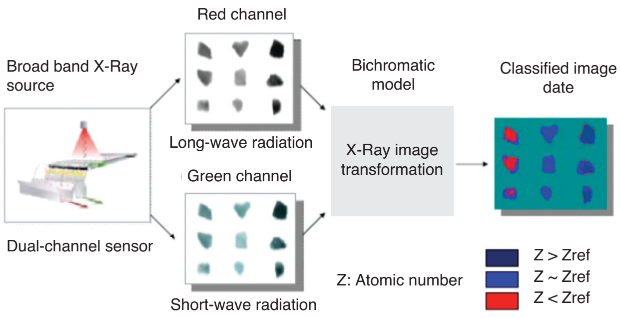


Figure 2. DE-XRT sorting principle.[9]

Table I

The electromagnetic spectrum and the different sensors available for sensor based sorting in mineral processing (Harbeck, Kroog, 2008)[5]

Radiation	[m]
	10^{-12}
Gamma-radiation	10^{-11}
	10^{-10}
X-ray	10^{-9}
	10^{-8}
Ultraviolett (UV)	10^{-7}
Visible light (VIS)	10^{-6}
	10^{-5}
Near Infrared (NIR)	10^{-4}
Infrared (IR)	10^{-3}
Microwaves	10^{-2}
	10^{-1}
Radio waves	10^{1}
	10^{2}
Alternating current (AC)	10^{3}
	10^{4}

Sensor/ Technology	Material Property	Mineral Application
RM (Radiometric)	Natural Gamma Radiation	Uranium, Precious Metals
XRT (X-ray transmission)	Atomic Density	Base/Precious Metals Coal, Diamonds
XRF	Visible Fluorescence under X-rays	Diamonds
COLOR (CCD Color Camera)	Reflection, Brightness, Transparency	Base/Precious Metals Ind. Minerals, Diamonds
PM (Photometric)	Monochromatic Reflection/Absorption	Ind. Minerals, Diamonds
NIR (Near Infrared Spectrometry)*	Reflection, Absorption	Base metals Industrial Minerals
IR (Infrared cam)*	Heat conductivity, heat dissipation	Base Metals Industrial Minerals
MW (heating in conjunction with IR)*	Sulfides & Metals heat faster than other minerals	Base/Precious Metals
EM (Electro-Magnetic sensor)	Conductivity	Base Metals

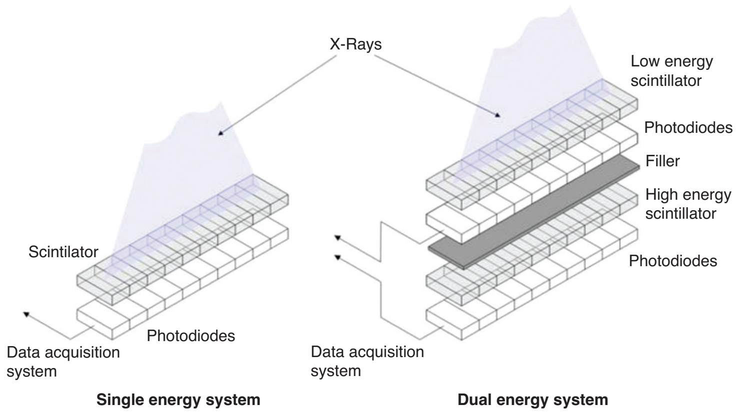


Figure 3—Single-energy vs. Dual-energy X-ray sensing principle

Figure 2 shows an example of iron ore pieces with different iron content varying from low to moderate or high grade ore (from left to right). The image on the right displays a colour-encoded classification of the pixels based on densities. This illustrates that the ore pieces can be classified into categories of different iron content.

The sensor's high resolution of 0.8 mm or 1.6 mm (depending on the model) is also used to evaluate the particle shape, particle size, material thickness, and texture of the gray-scale image, which represents inclusions of material of various densities. This X-ray transmission image processing thus provides a highly efficient sensor system for classifying different materials/minerals.

DE-XRT test work

Deshaling of coal from Witbank Coalfields, South African[10]

A prescreened –40 mm +20 mm, 2 ton run-of-mine sample from the Witbank coalfields was tested, the XRT sorter pilot plant at Mintek, Randburg South Africa during April 2006.

For comparative purposes, a standard float-sink analysis was conducted. A representative sub-sample of 100 kg was removed from the bulk sample for heavy liquid separation at cut points increasing in 0.1 increments from 1.3 to 1.8. The mass of each fraction produced was weighed and retained for as references for X-ray sorting test work.

The washability data presented in Figure 4 and Table II indicate that a significant proportion (~50%) of the sample lies within an SG range of -1.6+1.5. Shale material with SG greater than 1.8 represents only 0.42% of the feed sample. In addition, 25.04% of the sample will report to the coal product at a cut point of 1.35, resulting in a product with an ash content of 10.3%.

The DE-XRT tests were run on a Commodas PRO Secondary XRT belt 1200 sorter (Figure 5), which can handle a size range -60mm +10mm at 40 to 50 t/h. A 55 kW compressor with an operating pressure of 8 bar was used.

Figure 6 presents line-scan images of coal rich (SG =-1.3) and shale rich (SG= +1.7) material.

The atomic density of shale (consisting of Si, Al, Ca, and other elements) is depicted as a dark dray in the X-ray image. The combined high-energy and low-energy level X-ray images show a blue coloured simulated DE-XRT image.

In comparison, coal is composed mainly of carbon, has a lower atomic density, and shows as a red simulated DE-XRT image. The sorting program can thus be adjusted by defining various percentages of blue within each particle. Different sorting cut points were tested by changing the sensitivity of the sorting algorithm.

As expected, the cut point of the separation is controlled by the sensitivity of the programme as illustrated in Figure 7. For example, at a sensitivity of 75% blue, a cut point of approximately 1.6 is attained. This cut is reduced to approximately 1.5 and 1.45 for sensitivities of 50% and 25%, respectively. As the sensitivity is increased, so the efficiency

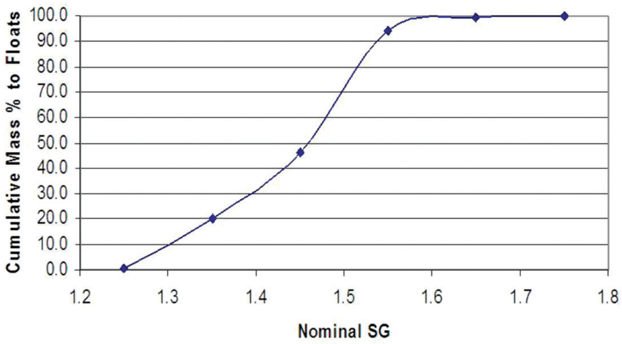


Figure 4—Washability curve based on data presented in Table II

Table II

Washability data

SG class	Nominal SG	Mass (%)	Cum mass (%)	Reconstituted ash analysis Discrete (%)	Reconstituted ash analysis Cumulative (%)
-1.3+1.2	1.25	0.63	0.63	8.20	8.20
-1.4+1.3	1.35	19.65	20.28	10.30	10.24
-1.5+1.4	1.45	26.25	46.53	20.25	15.89
-1.6+1.5	1.55	47.73	94.26	26.28	21.15
-1.7+1.6	1.65	5.09	99.34	41.13	22.17
-1.8+1.7	1.75	0.65	100.00	54.53	22.38
		100.00		22.38	

Figure 5—PRO secondary XRT belt 1200 sorter at Mintek

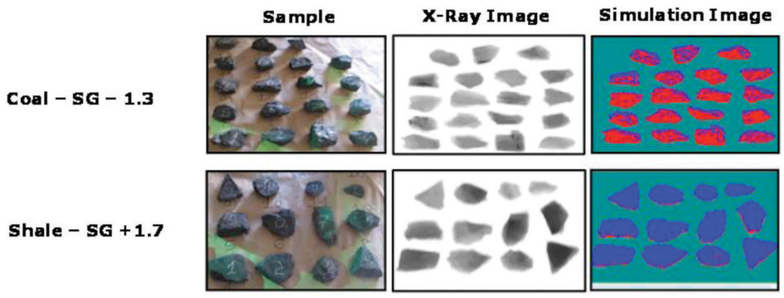


Figure 6—Line-scan images of coal and shale with simulation analysis

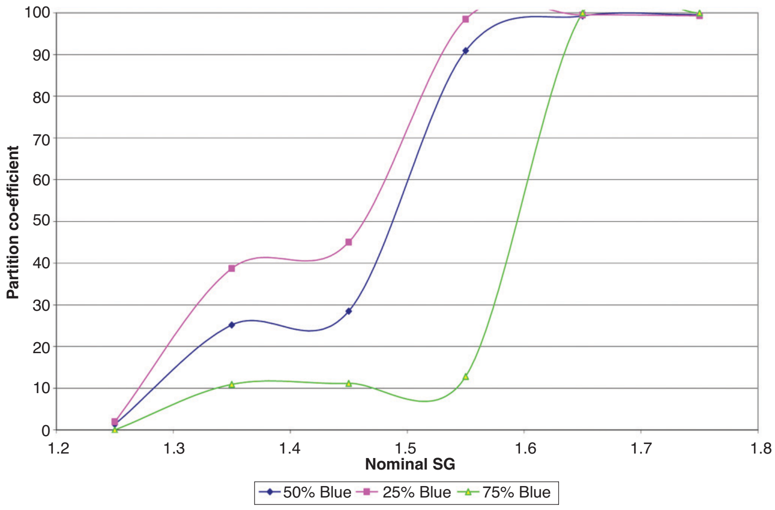


Figure 7—Partition curves for three X-ray sorting tests

of the separation is improved. It is also noted that misplacement of lower SG material (SG less than 1.5) occurs for all three tests. This is largely attributed to mechanical misplacement during the sorting process. Ash content analysis was conducted on the products originating from the sorting test at sensitivity of 75%.

Table III indicates that the sample could potentially be upgraded from 22.38% ash to 16.70% ash. This could be further improved upon by reducing sensitivity further.

Further test and trial runs in various size ranges resulted in typical performances of XRT sorting of Witbank coalfields' coal as shown in Table IV. These results again show a significant reduction of ash content (from 26.2% to 16.56%) and an improvement in the calorific values of the product by using DE-XRT. Samples for this test work were run at throughputs up to 80 t/h.

Separating coal and torbanite

Torbanite causes problematic contamination at some of South Africa's coal mines. A coal/torbanite (see image in Figure 8) product mix is neither suitable for firing power stations nor

Table III

DE-XRT sorting results at sensitivity 75% blue

		Product distribution			Ash content		
SG class	Nominal SG	Accept stream (coal)	Reject stream (shale)	Reconstituted feed	Accept stream (coal)	Reject stream (shale)	Reconstituted feed
-1.3+1.2	1.25	0.63	0.00	0.63	8.20	0.00	8.20
-1.4+1.3	1.35	19.57	0.08	19.65	10.20	36.20	10.30
-1.5+1.4	1.45	21.18	5.07	26.25	12.60	52.20	20.25
-1.6+1.5	1.55	40.63	7.10	47.73	22.10	50.20	26.28
-1.7+1.6	1.65	0.01	5.08	5.09	8.50	41.20	41.13
-1.8+1.7	1.75	0.00	0.65	0.65	0.00	54.60	54.53
		82.02	17.98	100.00	16.70	48.32	22.38

Table IV

DE-XRT sorting results at different size ranges

-53 +20mm	Mass %	% Ash	Cv (mJ/kg)
Feed	100	24.12	24.23
Product	75.2	16.11	27.29
Waste	24.8	48.49	14.94
-75 +53 mm	**Mass %**	**% Ash**	**Cv (mJ/kg)**
Feed	100	25.76	23.91
Product	82.5	16.82	27.11
Waste	17.5	67.88	8.83
-100 +75 mm	**Mass %**	**% Ash**	**Cv (mJ/kg)**
Feed	100	29.71	22.77
Product	80.6	16.67	27.30
Waste	19.4	83.85	3.95
Reconstituted combined results			
-100+20 mm	**Mass %**	**% Ash**	**Cv (mJ/kg)**
Feed	100	26.20	23.73
Product	79.6	16.56	27.21
Waste	20.4	63.84	10.14

Figure 8—Coal (left) and torbanite (right)

suitable for export coal. However, this type of oil shale contains valuable smokeless fuel which can be pyrolized and converted liquid fuel.

The densities of both coal and torbanite are similar, therefore density separation technologies such as DMS or jigging does not work. A comprehensive research programme to test all possible sensors concluded that the best suited technology was Dual-Energy XRT. Figure 9 shows the clear differentiation among coal, shale, and torbanite in the XRT line-scan images.

Figure 10 shows the test run on the XRT pilot plant at Mintek. In the first pass clean coal was separated from a shale/torbanite mix. The torbanite and shale were separated in the second run.

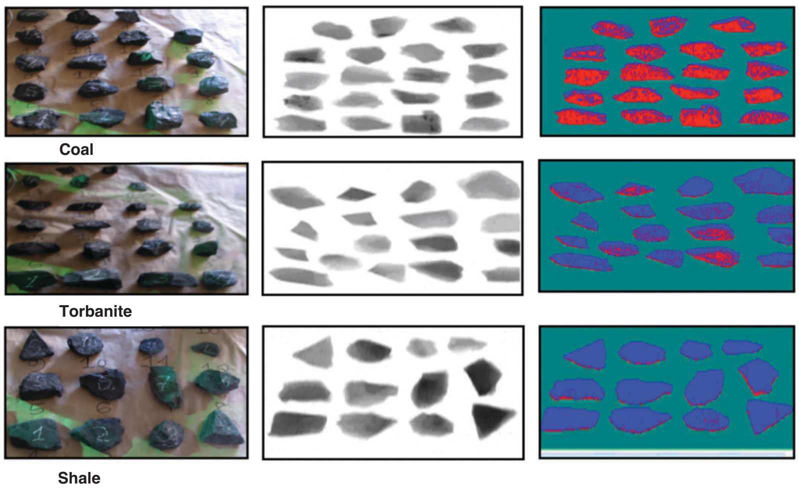


Figure 9—XRT line-scan images of coal, torbanite, and shale

Figure 10—Coal, torbanite, and shale separation on an XRT sorter

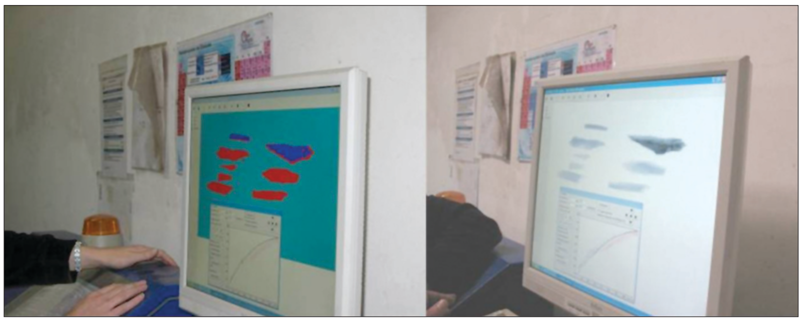


Figure 11—DE-XRT imaging and simulation

Removing pyritic sulphides from lignite, Texas, USA

A 500 kg lignite sample collected from various collieries in Texas, USA, was tested in the lab facilities at Commodas in Wedel, Germany in November 2007. The objective of these tests was to determine the effectiveness of DE-XRT for removing pyritic sulphides (and also the removal of mercury) to produce clean power station lignite. Figure 11 shows the X-ray images of the lignite and contaminant samples as well optimization of the sorting algorithm.

Figure 12 illustrates the combined low- and high-energy level X-ray images (classified image) of lignite samples showing various levels of contamination (shale) and pyrite inclusions, which are composed of denser material than the carbonaceous lignite. Coal/lignite is depicted by lighter gray shades in the X-ray image shown on the right and left in the classified image on the red.

The results in Table V clearly show that DE-XRT sorting can effectively remove and reduce pyritic sulphur in lignite. With the separation of pyritic sulphides locked up in lignite, mercury levels have also dropped significantly (there seems to be a correlation between pyrite and mercury). The optimal cut-off settings need to be determined, which should maximize the pyrite removal with minimal BTU losses.

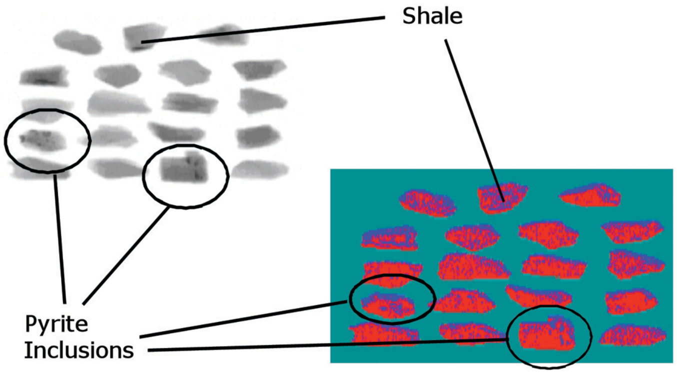


Figure 12—DE-XRT images of lignite, pyrite inclusions, and shale

Table V

DE-XRT removal of pyrite at various settings

Setting 2%							
Run 1	**kg**	**Yield**	**% Ash**	**% Sulphur**	**BTU**	**% FeS**	**% Hg**
Feed	50.86	100%	15.23	1.54	11078	0.50	0.14
Product	37.96	75%	13.41	1.18	11243	0.14	0.06
Waste	12.9	25%	18.00	2.24	10693	1.24	0.32
% Improvement			-11.95%	-23.38%	1.49%	-72.00%	-57.14%
Setting 10%							
Run 3	**kg**	**Yield**	**% Ash**	**% Sulphur**	**BTU**	**% FeS**	**% Hg**
Feed	87.94	100%	9.70	2.37	11412	1.31	0.24
Product	82.3	94%	7.29	1.39	11724	0.20	0.05
Waste	4.64	5%	40.22	14.69	6855	10.23	1.60
% Improvement			-24.85%	-41.35%	2.73%	-84.73%	-79.17%
Setting 15%							
Run 4	**kg**	**Yield**	**% Ash**	**% Sulphur**	**BTU**	**% FeS**	**% Hg**
Feed	145	100%	10.78	1.68	11392	0.48	0.14
Product	139.06	96%	10.33	1.45	11421	0.26	0.11
Waste	5.94	4%	33.64	14.47	7752	9.41	1.60
% Improvement			-4.17%	-13.69%	0.25%	-45.83%	-2143%

Pilot plant

In March 2010 a new PRO secondary XRT C 1200 sorter plant was installed and commissioned at the stock yard at Arnold Power Station shown in Figure 13. This dry XRT coal sorter is a chute-fed design which operated at capacities of up to 170 t/h.

The variation in throughput depends mainly on three factors:

- The amount of waste contained in the feed has a direct relation to the compressed air consumption; the less the waste, the higher the tonnage
- The size range—the ideal size range for sorting is at a 3:1 ratio. For this application -120+40 mm and -40+ 12 mm would be practical
- The relative density of the material; at a SG of 1.4–1.6 the coal throughput will be less than other typical mineral ores at the same volume.

The first results of the bulk deshaling test work are shown in Table VI. Especially in the coarse size fraction, XRT sorting showed good results in deshaling as well as improving the sulphur content of the product. These tests were also run in weather conditions varying from dry to heavy downpours; this had no effect on the performance of the sorter.

Conclusion

Sensor based sorting technology, which also includes DE-XRT, is gaining more and more significance in the mining and mineral process industry. Research and test work done on a variety of different coal types have proven to be successful in separating shale and pyrite-bearing coal thereby producing clean coal for further use. The DE-XRT sensor can also clearly differentiate between coal and torbanite, enabling a dry sorting process to produce two clean commodities. The sorter application is ideally suited for coarse coal beneficiation including a particle size range between -120mm +12.5 mm with throughputs of 150–80 t/h. A pilot plant at Arnot Power Station is currently operated in production mode to prove its robustness and reliability in a real operational environment. Ideally such a dry sorting process should be positioned as close as possible to the coal mine/pit to reduced transport cost and unnecessary crushing of shale and stone. The XRT sorting technology has good potential to become an integral component of future dry coal cleaning plants.

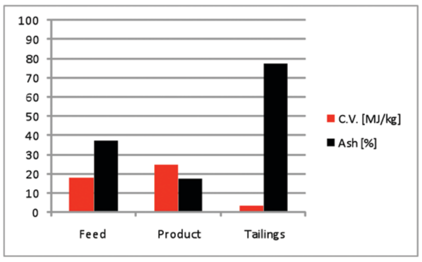
Figure 13—XRT sorter pilot plant at Arnot power station

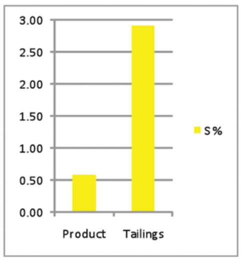
Table VI

Bulk deshaling test results from pilot plant at Arnot power station

120tph -100+60mm

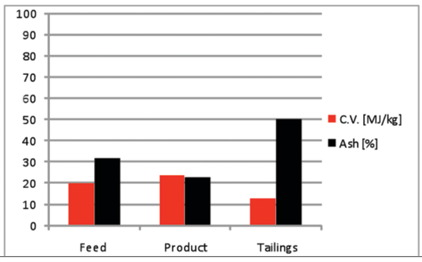
		Sample Mass kg	Ash [%]	C.V. [MJ/kg]	S [%]	
Feed	Calculated	86.70	37.3	17.9	1.34	
Product	Measured	58.32	17.8	24.96	0.58	
Tailings	Measured	28.38	77.5	3.26	2.91	*Yield* 67%

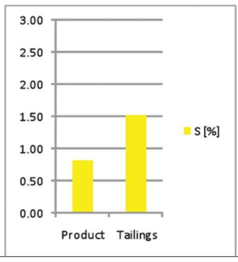




60tph -50+12.5mm

		Sample Mass kg	Ash [%]	C.V. [MJ/kg]	S [%]	
Feed	Calculated	19.50	31.9	20.1	1.06	
Product	Measured	12.96	22.7	23.83	0.83	
Tailings	Measured	6.54	50.2	12.76	1.52	*Yield* 66%





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