Evaluation of beneficiation options for recovery of ultrafine thermal coal

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Abstract

Recent requirements to reduce thermal coal plant emissions, and ultrafine coal's tendency to produce these emissions due to its typically high ash and moisture contents have limited the use of ultrafine coal. Ultrafine coal in beneficiation plants are usually either disposed of in tailing ponds at a loss in combustible material or disposed of by blending with coarser higher-grade products, resulting in a reduction in marketed product quality. A study of the options for processing ultrafine coal, consisting of < 200 µm hydrocyclone overflow, with 38.8 percent ash content is presented here. Ultrafine coal was processed based on 200-µm sieve bend and 10-µm hydrocyclone classifications, enhanced gravity separation (EGS) and froth flotation concentration as well as combinations of these. Yield, combustible material recovery (CMR) and product humidity were evaluated as test results.

Depending on the processing applied, product ash content could be reduced up to 49.7 percent, and up to 95.8 percent CMR of the actual run of mill feed could be attained. All of the processing options analyzed could reduce produced thermal electric plant emissions due to ash and moisture from 22 to 38 percent of the actual unprocessed ultrafine coal product.

Froth flotation was found to be the optimal process, yielding a product with the lowest ash content attained of 19.5 percent and CMR of 92.3 percent. Being the most versatile of the processes evaluated, it is capable of producing coal with varied ash contents but is subject to potential variations in coal flotability. The most complicated of the processing options, a combined sieve bend recovery of the > 200 µm fraction and EGS processing of the 10 to 200 µm fraction was found to be the next best option, attaining a combined 90.1 percent CMR and 25.0 percent ash content.

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Introduction

Municipal, regional and national objectives to reduce fossil fuel combustion emissions and their effects on air quality and global weather changes are affecting thermal electric plant operations. Plans and regulations such as President Obama's Clean Power Plan (U.S. Environmental Protection Agency, 2015), the European Directive 2010/75/EU (European Commission, 2010) and China's proposed Enhanced Actions on Climate Change (Wei, 2015) are of major significance to thermal electric plant operations. Although thermal plant efficiencies depend in large part on the losses of heat by plant components, the ash and humidity contents of thermal coal invariably reduce plant efficiencies and increase emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x) and dust.

Any noncombustible material present in thermal coal will result in higher CO_2 emissions per unit of energy produced. Since no particle emission control can be totally effective, it is to be anticipated that any reduction in coal ash content will also result in reduced particle emissions. Kurose, Ikeda and Makino (2001) reported that NO_x emissions also increase with coal ash content. The effect of coal moisture content during combustion is complex. Kurose, Ikeda and Makino (2001) showed that an increase in coal moisture content significantly reduces thermal NO_x to total NO_x production, and Bosoaga et al. (2006) showed that it tends to reduce NO_x emissions. Since the humidity, pyrite and ash content of thermal coals directly affect thermal electric plant efficiencies and emissions, minimizing these factors should facilitate, at least in part, compliance with thermal electric plant emission limits. This, in turn, would affect the specifications and prices of the coal preparation plant products.

Operations at coal preparation plants dedicated to the pro-

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duction of thermal steam coal are based on classification and density separation technologies for coal particle sizes greater than about 0.1 mm. Coal particles with size smaller than 0.5 mm and especially those smaller than 200 μm, designated here as ultrafine, invariably have high ash contents. Since the ultrafine coal is not suited to conventional high-volume, low-cost gravity separation methods, operators must select between the alternatives of disposing in tailings ponds at a loss in combustible material recovery or blending with coarser, lower-ash coal products with a net reduction in thermal potential.

This paper is presented to demonstrate that coal washing plants now limiting production to thermal electric coal but which originally also produced other products such as those for heating and metallurgical markets might benefit from processing their ultrafine fractions. Presented here are the results of tests conducted to evaluate the potentials of six ultrafine runs of mill coal processing options based on blending with coarser, lower-ash products; classification; enhanced gravity separation: froth flotation; and combinations of these. Although there can be significant variations in ultrafine coal properties between different plants, a relatively typical sample of ultrafine coal was obtained from the Batan plant of Hulleras del Norte S.A. (Hunosa) that is processing coal combined from eight mine sites. The operations there originally used jigging and froth flotation to supply coal to heating, thermal electric and metallurgical markets but is now limited to supplying the thermal electric market.

Product yields, combustible mineral recovery (CMR) and additional plant equipment requirements for the processing options reviewed are provided.

Materials and methods

Characterization of the ultrafine product sample. A sample of ultrafine coal pulp was obtained from Hunosa's coal preparation plant. Operations at the plant had included crushing; screening and hydrocyclone classification; gravity and froth flotation concentration; and dewatering by centrifuges, rotary disk filters and plate and frame filter presses. Now, it only produces thermal coal based on classification, dense-medium separation, and recovery of fines by filter presses (Fig. 1). The preparation process includes offsite screening to remove material with particle size smaller than 100 mm (99 percent gangue) and onsite screening at 14 mm with the overflow processed in a dense-medium drum separator. The screen underflow passes to a classifying hydrocyclone to produce a 0.2 to 14 mm fraction, which is treated in two dense-medium cyclones. The < 200 μm hydrocyclone fraction constituting the ultrafine of this study is dewatered using two large plate and frame filter presses operating at some 11 percent of capacity. All plant waste streams and rainwater runoffs from the plant site along with any excess slurry are fed to a storage tank and are fed back as required into the plant through the filter presses.

A 400-L sample was obtained in 20 containers collected at 20-minute intervals from the plant's ultrafine collector to the thickener that feeds the filter press. The sample was homogenized and divided into representative fractions for analysis and subsequent tests.

The ultrafine fraction is typically about 40 percent ash, 4,400 to 4,700 kcal/kg, and about 0.9 percent total sulfur, with the vast proportion organic and not amenable to mineral separation (Fernandez, 2013). Ultrafine coal is disposed of by blending with the coarser coal dense-medium separation products to produce a thermal coal complying with a local thermal electrical plant's requirement. Although this fraction has lower ash content than the ultrafines of many coal beneficiation plants, the results were anticipated to be indicative of the results that would be obtained with those materials.

The ultrafine stream was found to have 73.5 g/L of solids with ash content of 38.75 percent, constituting 7.15 percent by weight of the slurry. Ash content analysis of the particle size fractions obtained by sieving and hydrocyclone classification of

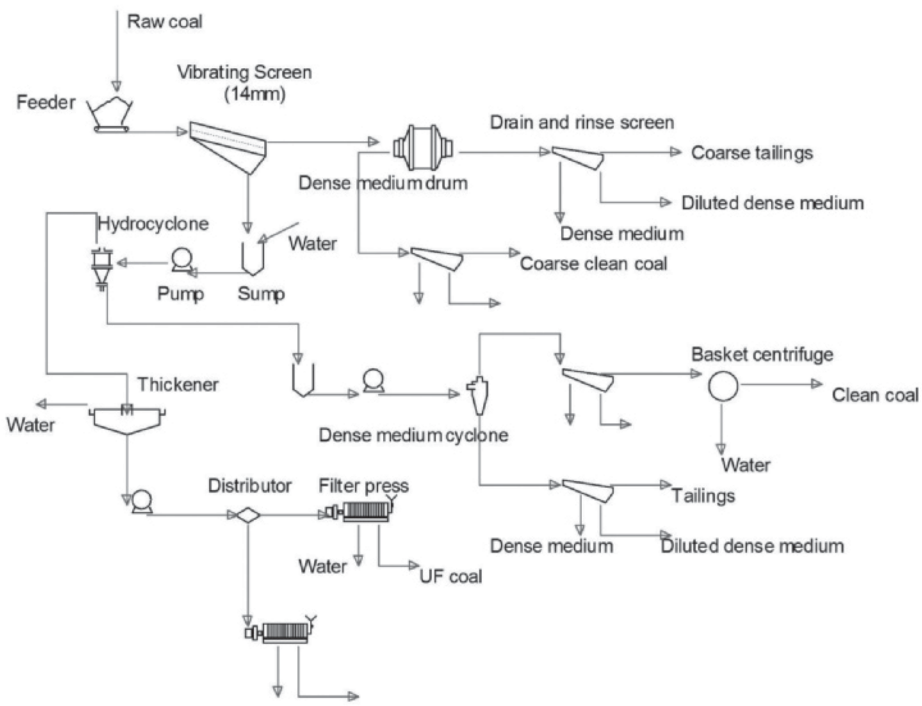

Figure 1 — Generalized flowsheet of the washing plant.

the < 45 μm fraction (Table 1) indicate an exponential increase in ash content with reduction in particle size.

The exponential relationship between a given particle size, x, in μm, and the ash content, as a percentage, associated with the particle size is given by:

$$\text{Particle size ash content} = 100.23x^{-0.2744} \qquad (1)$$

This relationship was found to have a correlation factor R^2 of 0.96. The data indicate that the particle ranges present in the ultrafine that are potentially most suitable for combustion are limited to those coarser than about 10 μm. The data also suggest that the classification processes probably lose some relatively low-ash coal particles to the hydrocyclone overflow, or that some fine coal is lost from the centrifuge driers or that it is carried into the system by water runoff from the coal storage piles.

Processing models evaluated. Based on the ultrafine pulp feed-dilution, particle-size-distribution and ash-content-variation characteristics, six options for processing the ultrafine stream were selected. These were based on classification, centrifugal-density-separation and froth-flotation process options. The six options are as follows:

- *Option 1: The "status quo."* This represents a simple means of disposing of this fraction, which would otherwise have to be stored in hilly terrain. Because the filter-pressed ultrafine product is relatively plastic and tends to liquefy on contact with rainwater, its disposal in this type of terrain presents serious geotechnical risks. This operation was achieved at a particularly low cost as the existing infrastructure of the plant included two large plate and frame filter presses previously used to dewater flotation coal and tail fractions.
- *Option 2: Desliming at 10 μm.* Because the < 10 μm fraction of coals is invariably high in ash content, the elimination of this fraction represents a simplistic option with the feed of waste and coal products to separate filter presses. Particle size classification at 10 μm with 4- or 6-in. hydrocyclones is widely conducted in many mineral processing operations and suitable equipment is readily available. Additions to the plant (Fig. 2) are based on the underflow from a nest of a hydrocyclones being pumped directly or gravity fed to an additional feed tank dedicated to a single filter press while the overflow goes to the existing thickener prior to being fed to the other filter press.
- *Option 3: > 200 μm recovery.* The > 200 μm fraction with 19.1 percent ash content constitutes a higher-value thermal electrical product, and the < 200 μm fraction still meets the specifications of the company's own fluidized-bed thermal electric plant. The > 200 μm fraction could be recovered by sieve bend classification fed by gravity to the basket centrifugal drier along with the dense-medium cyclone floats (Fig. 3). The < 200 μm fraction could be treated as in the "status quo" procedure. This option is a solution with particularly low capital and operating costs while generating higher returns. In the case of Hunosa's operations, like other coal washing plants located in close proximity to some thermal electric plants, if combustion of the < 200 μm fraction produces excessive emissions, it could be transported to a combined coal processing and thermal electric plant tailings site.
- *Option 4: ROM-enhanced gravity separation.* Enhanced

Table 1 — Ash content analysis of particle size fractions.

Particle size range (μm)	Ash content (%)	Weight (%)	Cumulative weight (%)	Cumulative ash content (%)
> 800	12.89	0.29	100	38.75
500-800	15.78	2.02	99.71	38.83
355-500	16.82	3.23	97.69	39.31
315-355	20.42	1.32	94.46	40.07
250-315	22.36	3.25	93.14	40.35
200-250	23.74	1.82	89.89	41
125-200	28.99	7.56	88.07	41.36
71-125	28.43	13.37	80.51	42.52
45-71	31.06	10.36	67.14	45.33
10-45	43.2	41.04	56.78	47.93
<10	60.27	15.74	15.74	60.27

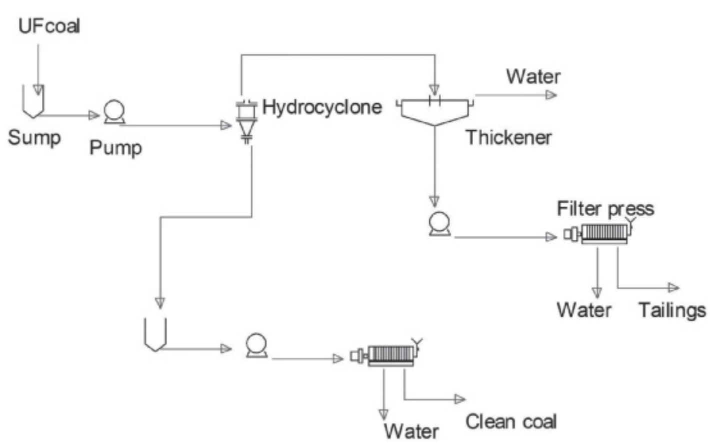

Figure 2 — Option 2 version of the ultrafine coal circuit.

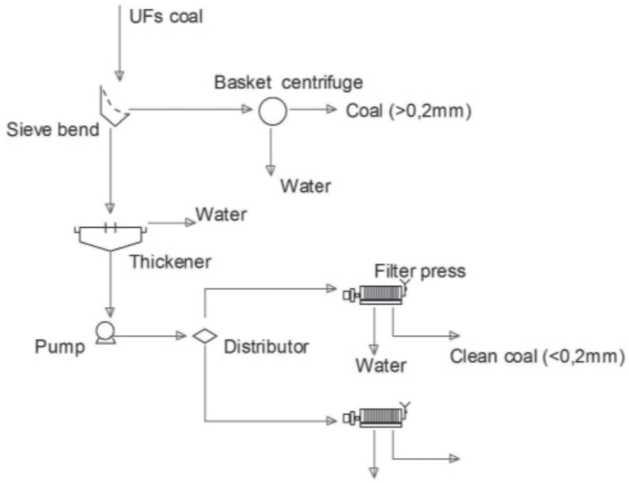

Figure 3 — Option 3 version of the ultrafine coal circuit.

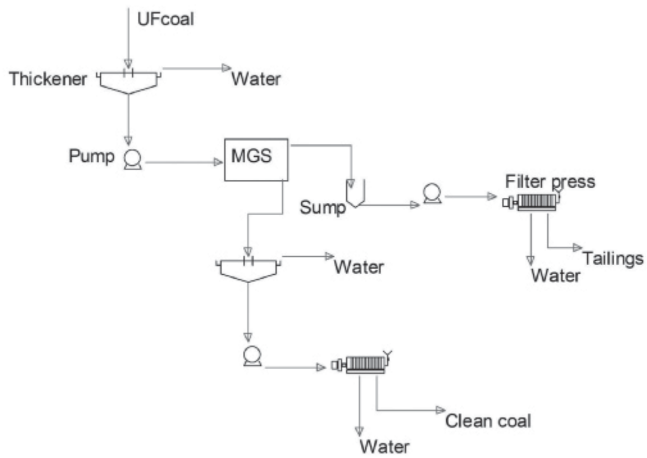

Figure 4 — Option 4 version of the ultrafine coal circuit.

gravity separator (EGS) processes are frequently considered for the treatment of ultrafine particles. Water-only cyclones (WOC) are widely used in the processing of coal particles, typically those < 600 μm in size. However, Majumder and Barnwal (2011) showed that the efficiency of WOCs in separating particles by density decreases significantly below 75 μm. WOCs are not considered practical for the sample as more than 50 percent of the plant's ultrafine are between 10 and 75 μm.

Several EGS devices, such as the Multi-Gravity Separator (MGS), Falcon Concentrator, Knelson Concentrator and Kelsey Jig, have been developed for enhanced gravity separation, and a considerable volume of research results have been reported. The general operating principles of these devices were described by Luttrell, Honaker and Phillips (1995), Gagarin, Gyul'maliev and Tolchenkin (2008), Kawatra and Eisele (2001), Honaker and Ozsever (2003), Honaker and Das (2004) and Majumder and Barnwal (2006).

Some of the most notable of the investigations of coal beneficiation using the Falcon Concentrator are those by Honaker et al. (1995), Honaker, Wang and Voyles (1996), Honaker, Wang and Ho (1996), Honaker (1998), Honaker and Wang (1998), Honaker, Mohanty and Govindarajan (1998), Honaker et al. (2001), Honaker and Das (2004), and Oruç, Özgen and Sabah (2010). Riley, Firth and Lockhart (1995), Luttrell, Honaker and Phillips (1995), and Honaker and Wang (1998) reported this separator as suitable for ultrafine coal as fine as 37 μm, but Oruç, Özgen and Sabah (2010) reported it as most suitable for separations involving particles coarser than 75 μm. Studies by Honaker, Singh and Govindarajan (2000), Patwardhan et al. (2000) and Chugh et al. (2000) had highly favorable results for the beneficiation of 44 to 1,000 μm coal recovery from tailings using < 44 μm magnetite-based dense media. This option should entail the highest capital and operating costs among the EGS methods.

Significant work on the Knelson Concentrator had been reported by Honaker, Das and Nombe (2005), Majumder, Tiwaria and Barnwala (2007) and Öney and Tanrıverdi (2012). Similarly, favorable results for the beneficiation of ultrafine coal with the MGS were reported in Rao and Bandopadhyay (1992), Venkatraman et al. (1995), Goktepe al. (1996), Rubiera, Hall and Shah (1997) and Menendez et al. (2007). In Menendez et al. (2007), effective coal separation with the MGS was reported to require the feed to be deslimed at 10 μm.

Although the compilation by Luttrell et al. (1995) of ultrafine coal beneficiation results with the principal EGS devices indicate that all of those tested had significant potential, no comparative tests have been reported with the different devices under optimum conditions and with ultrafine coal feeds of different degrees of coal liberation and grain size distribution.

The concentration processes employed in these devices differ. The Falcon and Knelson concentrators are the most common EGS devices and operate on densimetric settling in a fluidized bed under up to +300 G and 60 G centrifugal forces, respectively. The MGS has the advantage of using flowing film densimetric separation, mimicking shaker table separation, which Burt and Mills (1984) indicated was the most effective density separation process. It is suspected that similar ultrafine coal feed preparation is required for all EGS devices and that relatively similar results would be attained with the MGS, Falcon Concentrator and Knelson Concentrator. Because of our greater experience with the MGS, this device was selected for this study.

Processing requires prior thickening of the pulp to an adequate solids content (Fig. 4). The coal product has low water content and can be fed directly to one filter press, with the rejects fed to a thickener and then to the other filter press.

- *Option 5: > 200 μm recovery and deslimed enhanced gravity separation.* Option 4 is based on the multi-gravity separation of the entire ultrafine stream. In Menendez et al. (2007), the MGS was indicated as suitable for processing ultrafine coal provided the < 10 μm fraction is eliminated. Furthermore, > 200 μm coal particles were observed to tend to report to the dense MGS product. Option 5 is therefore based on the MGS processing of a 10/200 μm stream that had been sieve bend screened and hydrocycloned, with the wastes and

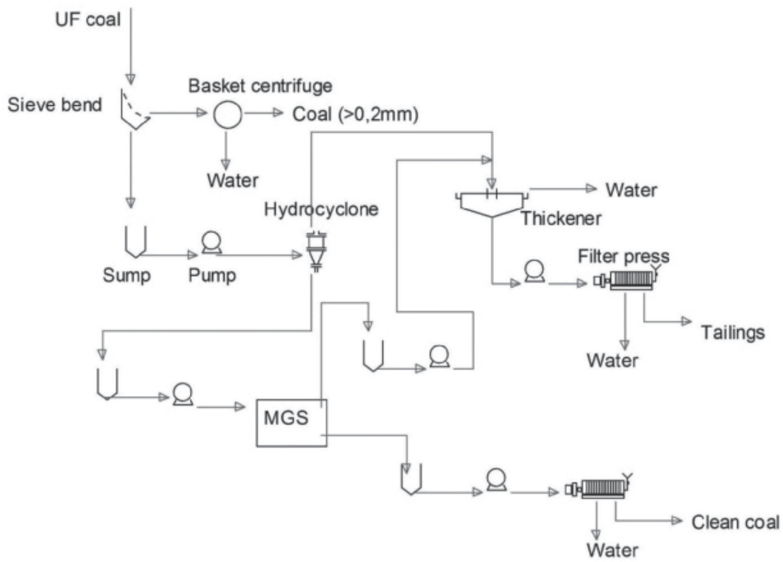

Figure 5 — Option 5 modified version of the ultrafine coal circuit.

coal fed to separate filter presses (Fig. 5).

- *Option 6: Froth flotation.* Froth flotation was considered to be potentially the most metallurgically efficient method for treating the entire range of particle sizes in the ultrafine fraction. Froth flotation of this particle size range has been extensively described in the literature, for example, by Davis et al. (1995), Firth (1999), Jameson (1983), Kawatra and Eisele (1987, 2001), Laskowski and Poling (1995), Meenan (1999), Osborne (1988) and Rao, Govindarajan and Barnwal (1995). This option depends on the ultrafine coal being hydrophobic. Oxidized or poorly liberated particles may not respond well to this process. Given the moderately low content of the < 10 μm fraction in the ultrafine coal, elimination of this fraction was not considered necessary. The investigations by Chugh et al. (2000) indicated that some of the ultrafine coal tailings tested required elimination of adhering clays and, even then, not all were greatly amenable to froth flotation. The froth flotation tests were conducted with a standard single cell D-12 Denver device (Fig. 6). It is anticipated that results obtained with a Jameson or column flotation cell could be slightly better than those reported here due to the use of wash water to remove gangue entrained in the float bubbles.

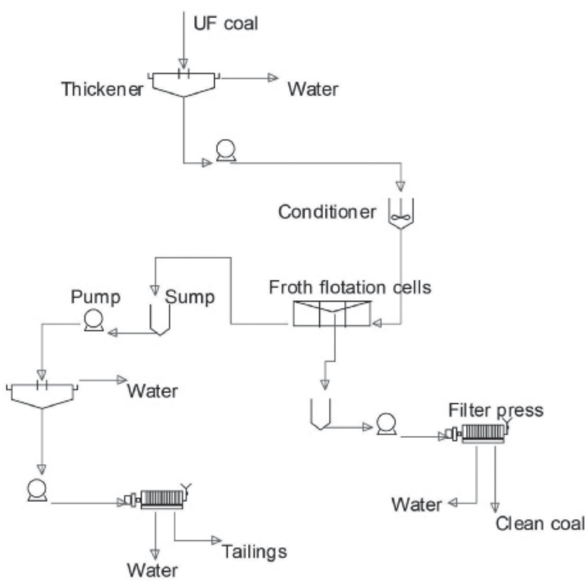

Figure 6 — Option 6 version of the ultrafine coal circuit.

Evaluation procedure. The samples provided were homogenized and their ash contents determined according to the ISO 1171 procedure (International Organization for Standardization, 2010). Thickener sizes were calculated according to the conservative procedures of Talmage and Fitch (1955).The scaling up of enhanced gravity separations obtained with a Mozley MGS C900 laboratory device to the industrial-scale MeGaSep were based on data courtesy of Daniel (2007). Laboratory particle size classification by hydrocycloning and sieve bends at 200 μm were not feasible, and determination of the products obtainable for such classifications were derived by calculations based on published and manufacturer specifications or partition curves. Froth flotation tests were conducted only with the raw ultrafine samples, as the approximately 15 percent < 10 μm content was deemed sufficiently low to not result in adverse demand for reagents. The plant's twin filter presses were operating at about 11 percent capacity, so to minimize capital investment, all < 200 μm coal concentrates were assumed to be dewatered in one and all the tails in the other.

Processing results

Hydrocyclone classification of an ultrafine slurry sample. Desliming of the ultrafine coal sample was conducted using a Mozley 2-in. hydrocyclone with an 1/8-in. apex. Analysis of the products (Table 2) indicates the overflow ash content to be 59 percent, which is close to the limit admissible for fluidized-bed electrical plants and is not considered to be a viable fuel unless transport costs are extremely low. No material in the overflow was retained on a 25 µm screen and laser diffraction particle size analysis indicated that all particles were ≤ 20 µm. A smaller hydrocyclone might result in a finer classification to produce an overflow with higher ash content but this would be at higher capital and operating costs.

Hydrocycloning yielded 83.55 percent in the underflow as a thermal coal product with CMR of 83.03 percent. This requires the addition of a pump to the hydrocyclones and another to feed an additional thickener.

Sieve classification of an ultrafine slurry sample. Calculations of the particle size distribution of a sieve bend classification at 200 µm obtainable and coarse product moisture content were based on data from Fueyo (1999) and Gupta and Yan (2006). Unclassified (fine) particles short-circuiting to the coarse product were calculated based on the direct proportion of < 200 µm particles in the feed water relative to the proportion of that water reporting to the coarse product

Prior hydrocyclone elimination of the < 10 µm fraction was not considered viable for preparing the sieve bend feed in the Option 3 scenario as the reductions of 0.04 percent in yield, 0.10 percent in ash content and 0.02 percent in CMR are negligible. Based on the coarse product calculated to have moisture content of 42 percent, the yield of this product fraction would be 16.83 percent of the total ultrafine with ash content of 22.41 percent. The > 200 µm product CMR obtained of the total ultrafine is 17.71 percent. This option requires the addition of a slurry pump to feed this fraction to the plant's centrifugal coal driers.

EGS processing of ultrafine slurry samples. Two options for the enhanced gravity separation of the ultrafine were considered based on the run-of-mine (ROM) feed and particle size classifications of this feed. These included enhanced gravity separation after thickening to a suitable solids concentration of the ROM ultrafine feed after separation of the > 200 µm fraction by sieve bend classification of the ROM feed as a separate product, and elimination of the < 10 µm fraction by hydrocycloning.

Elimination of the < 10 µm fraction was considered important as it was demonstrated in Venkatraman et al. (1995) and Menendez et al. (2007) that removing the clay fraction optimized MGS coal separations. EGS tests were conducted with the MGS C900 pilot-plant model in batch mode. Results were corrected for mass balance according to the manufacturer's instructions (Richard Mozley Ltd., 1992). The MGS operational variables of shake amplitude of 10 mm, shake frequency of 5.7 cps, pulp feed rate of 1.31 L/min and drum inclination of 5º were selected based on Venkatraman et al. (1995), Goktepe et al. (1996) and Menendez et al. (2007). Since the ultrafine coal sample had a coarser grain size distribution than the Asturian coal fines that we previously processed using a MGS, processing of the raw and deslimed samples were conducted with a drum rotation rate of 250 rpm rather than the optimum 280 rpm previously recommended in Menendez et al. (2007). Only wash water and pulp solids contents were varied in the tests conducted.

MGS processing produces a dense, high-ash product with relatively high solids content, typically about 60 percent, and a low-density, low-ash product with extremely low solids content, similar to that pumped to the filter press thickener in this study. The coal product will require the installation of a centrifugal pump feeding the thickener for subsequent filter pressing and a slurry pump feeding the tails to the other filter press.

MGS processing of the ROM ultrafine slurry sample. Tests showed that under the described operating conditions, for 30 percent slurry feed solids content, 1 L/min was the optimum wash water flow rate (Table 3). At rates of 0.85 and 2 L/min, product CMR increased, as did ash content. Greater slurry feed solids contents require larger wash water flows. But even under

Table 2 — Characteristics of the 2-in. hydrocyclone products of the ultrafine coal feed.

	Yield (%)	Ash content (%)	Slurry solids (%)	Solids, < 10 µm (%)	Solids, 10-25 µm (%)	Solids, > 25 µm (%)
Feed in slurry	100	38.75	7.15	15.74	26.58	57.68
Underflow	83.55	34.77	38.56	4.8	94.4	100
Overflow	16.45	58.97	3.64	95.2	5.6	0

Table 3 — Results of the MGS tests of the ROM ultrafine coal slurry.

Slurry solids content (%)	Wash water (L/min)	Product	Yield (%)	Ash content (%)	CMR (%)
30.00	0.85	Coal	90.82	34.25	97.50
		Tails	9.18	83.3	
30.00	1	Coal	86.05	31.83	95.79
		Tails	13.95	81.5	
30.00	2	Coal	91.69	34.76	97.67
		Tails	8.31	82.85	
32.44	1.6	Coal	81.13	28.82	94.28
		Tails	18.87	81.45	
32.44	2.88	Coal	90.18	34.14	96.97
		Tails	9.82	81.07	

Table 4 — Characterization of 10 µm to 200 µm MGS feed from the underflow of a hydrocyclone after sieve bend classification.

Particle size range (µm)	Ash content (%)	Weight (%)
250-315	22.36	0.10
200-250	23.74	0.23
125-200	28.99	11.05
71-125	28.43	19.63
45-71	31.06	15.23
25-45	33.41	19.71
10-25	48.28	33.88
<10	60.27	0.17
Total	36.64	100

Table 5 — Results of the MGS processing of deslimed, 10 µm to 200 µm ultrafine slurry.

Wash water (L/min)	Product	Yield (%)	Ash content (%)	CMR (%)
0.94	Coal	58.92	26.38	70.82
	Tails	41.08	56.5	
2.00	Coal	67.15	25.56	81.61
	Tails	32.85	65.72	
2.52	Coal	71.87	25.66	87.24
	Tails	28.13	72.21	
2.85	Coal	76.17	27.12	90.60
	Tails	23.83	75.82	
2.88	Coal	75.43	26.86	90.08
	Tails	24.57	75.26	

Table 6 — Froth flotation product ash content and yield versus flotation time.

Time (min)	Weight (%)	Cumulative weight (%)	Ash (%)	Cumulative ash (%)
1.5	4.6	4.6	16.04	16.04
3	10.1	14.7	14.9	15.26
4.5	9.6	24.3	14.24	14.86
6	8.3	32.6	13.81	14.59
7.5	5.5	38.1	13.73	14.46
9	4.9	43	14.78	14.50
10.5	6.3	49.3	17.19	14.84
12	4.1	53.4	20.32	15.26
13.5	7.6	61	22.74	16.20
15	3.8	64.8	29.44	16.97
16.5	3.0	67.8	46.37	18.27
18	0.8	68.6	47.17	18.61
19.5	1.7	70.3	57.23	19.54
Tails	29.7	100	84.21	38.75

the indicated conditions, the optimum product CMR obtained was 1.51 percentage points lower, although at a slight reduction of 3.01 percentage points in coal ash content to 28.82 percent.

Although this processing option represents a simple plant design modification, it requires substantially higher ROM slurry solids content, implying the need for an additional sedimentation tank, 19 m in diameter.

MGS processing of the 10 to 200 µm *ultrafine slurry sample.* Preparation of the ultrafine slurry by sieve bend classification to remove > 200 µm and < 10 µm particles resulted in a 76.4 percent yield of the ROM ultrafine coal to the MGS with ash content of 36.6 percent, as characterized in Table 4. MGS processing (Table 5) yielded an optimum ash content of 25.6 percent with a CMR of 90.6 percent. With 17.0 percent of combustible material loss to the hydrocyclone overflow wastes and 17.7 percent of the combustible material of the hydrocyclone underflow reporting to the coarse fraction of the sieve bend product, the resulting MGS product yielded a CMR of 72.4 percent.

Froth flotation of the ultrafine slurry sample. Direct batch flotation tests were conducted with 5-L samples of ROM ultrafine slurry with 20 percent by weight solids content. Optimum preparation of the pulp for flotation was found to be conditioning for two minutes with 218 g/t of kerosene followed by the addition of 70 g/t of methyl isobutyl carbinol (MIBC) frother with agitation for an additional two minutes. The froth product was collected at 90-second intervals until no more floats were produced. Flotation times determined in the laboratory tests were increased by a factor of 1.6 to correspond to industrial-scale operations, as recommended by Arbiter (1985).

The results indicate an optimum CMR of 92.34 percent with a product ash content of 19.54 percent, a reduction of 49.7 percent of the unprocessed ROM coal (Table 6). Figure 7 indicates that during the first 7.5 minutes of flotation, there was a progressive decrease in ash content of the recovered coal. This suggests that ultrafine gangue particles such as clay were also being recovered during this period. It is estimated that an optimum product might be obtained if the ultrafine slurry was deslimed at 10 µm, which would reduce the ash content to 15.2 percent but give an overall reduction in CMR of the ROM ultrafine slurry to 88.14 percent.

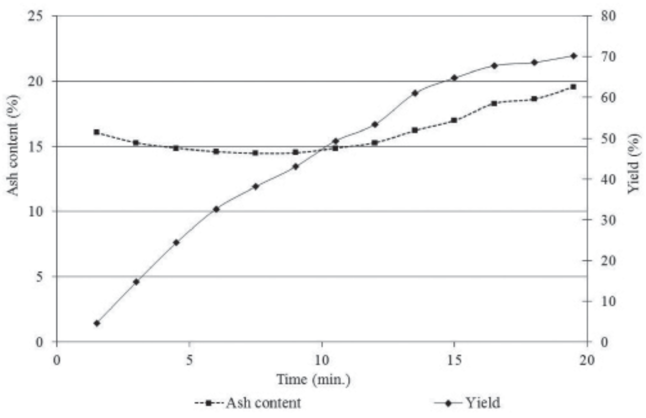

Figure 7 — Cumulative coal ash content and yield versus duration of froth flotation of ultrafine having 20 percent by weight solids content with 218 g/t kerosene and 70 g/t MIBC.

Table 7 — Comparison of the results.

Option	Option product	Yield (%)	CMR (%)	Ash content (%)	Mois-ture (%)	Noncombustible CO_2 emissions (m^3/t)	Combined product, noncombustible CO_2 production (m^3/t)
1	Unprocessed ROM coal	100	100	38.8	22	37.62	37.62
2	Deslimed > 10 µm	83.6	83.0	34.8	20	27.81	27.81
3	Sieve bend > 200 µm	16.8	17.7	22.4	16	22.21	29.45
	and <200 µm	83.2	82.3	42.1	24	30.92	
4	ROM MGS	86.1	95.8	31.8	19	26.65	26.65
5	> 200 µm sieve bend	16.8	17.7	22.4	16	22.21	24.11
	and 10/200 µm MGS	71.9	72.4	25.7	18	24.65	
6	Froth flotation	70.3	92.3	19.5	18	23.25	23.25

Discussion of ultrafine coal processing options

Modification of an existing processing circuit usually depends not only on optimization of the results attainable and the costs entailed but also on available in-house equipment, their compatibility with existing processing systems and the previous experience of personnel with them. Of the processing options tested, classification with hydrocyclones and sieve bends and concentration by direct froth flotation are common practices in coal preparation plants, and plant personnel may be familiar with them. Processing plants that have narrowed down product variety to thermal coal alone may still have suitable sieve bends and flotation cells in stock. Hydrocyclones to classify feeds at 10 µm are not typical of coal preparation plants. There is no substitute for sieve bends for classifying ultrafine coal, and the high ash content of ultrafine coal implies that these will require more maintenance due to the wear associated with the ash content. Residual kerosene and frother agents in the tailings from flotation cells may present environmental risks under certain local geographic and climatic conditions. It is also anticipated that despite the published results demonstrating the potential of enhanced gravity separators such as the Multi-Gravity Separator or the Falcon Concentrator, only an extremely limited number of coal preparation plants, if any, may have had any experience with these devices.

To compare these products as a thermal electric plant feed stock, the probable filter press product moisture content was determined based on a selection of the maximum values from tests with a laboratory Larox 25 filter and typical values as reported by Osborne (1988) and Rázumov and Perov (1985). The CO_2 generated due to the ash and humidity contents of the option products during combustion in a typical electrical plant operation were calculated based on highly simplified operating conditions, including ambient temperature of 21 ºC; all thermal energy above 300 ºC and none below this temperature is recovered; gas emissions are either water vapor or CO_2; the specific heats of the product ash, humidity (water), water vapor and CO_2 are 0.24, 0.99986, 0.47664 and 0.1823 kcal/kg ºC, respectively; and the heat of vaporization of water is 0.542 kcal/kg.

The results (Table 7) indicate that options 2 to 6 all produce coal with significantly lower potential CO_2 emissions. Hydrocyclone elimination of the < 10 µm results in 10 percent reduction in ash content, but the product is still relatively high in ash and moisture. CO_2 emissions due to reductions in product ash and moisture for this product are reduced 26 percent. The high ash content of 59 percent of the overflow still has a usable calorific value but cannot be used to reduce thermal coal emissions.

The most simplistic processing option of recovering a > 200 µm sieve bend product resulted in CMR of 100 percent and the obtaining of a higher-value, marketable standard thermal electric coal and a residual < 200 µm product that, as in the case of the < 10 µm hydrocyclone overflow product, has a usable calorific value but cannot be of value as a product for reduction of coal emissions. Nonetheless, it might still be used in the company's fluidized-bed thermal electric plant. The combined net calorific value of these products remains lower than that of the unprocessed product due to the increase in the combined product moisture content.

The use of MGS to process the ROM ultrafine coal resultsed in high CMR of 95.8 percent but there was low reduction of product ash (18 percent) and of moisture (3 percent). Coal losses were primarily due to coarse, low-ash coal reporting to the dense product fraction.

For Option 5, recovery of the > 200 µm fraction and desliming the EGS feed at 10 µm optimized products to achieve ash contents of 22.4 and 25.7 percent, respectively. A relatively high, combined 90.1 percent CMR was attained but with ash content of 25.0 percent. However, combustion of the combined process products generated 36 percent less CO_2.

Direct froth flotation of the ROM ultrafine coal produced the best results. It achieved CMR of 92.3 percent with product ash content of 19.5 percent. Of all the processing options, it had the lowest nonproductive CO_2 emissions. It is estimated that hydrocycloning of the flotation product to deslime it at 10 µm would probably reduce the ash content to about 15.2 percent but with an approximately 4.2 percent reduction in CMR. The high CMR indicates that the ultrafine coal tested was not oxidized. An oxidized or hydrophilic coal would not respond as effectively to flotation, and the CMR would be significantly lower.

Excluding the > 200 µm coal product, all the ultrafine filter press coal option products appear to have a polynomial relationship between moisture and ash content (Fig. 8). This relationship is given by:

$$\text{Humidity (percent)} = 0.0099x^2 - 0.2338x + 16.285 \quad (2)$$

It has a correlation factor (R^2) of 0.9992. Extrapolation of the equation indicates that the absolute minimum product filter press product moisture attainable from this ultrafine feed is on the order of 14.9 percent. This moisture is largely attributed to water between the product coal particles, that is, filter press product porosity, and to a lesser extent to some adsorption on the surface or within the structures of clay minerals present.

Except for water within the structure of mineral or rock particles in the coal product, a portion of the moisture present might be reduced by the use of an air blow drying device during filtration in the filter press. Since coal preparation and thermal electric plant storage of coal are almost invariably not in warehouses, ultrafine coal will readily absorb any precipitation. The only benefit of drying would be to reduce transportation costs.

Conclusions

Of the processing options tested to upgrade the quality of the ROM ultrafine coal from a 38.75 percent ash product, particle size classification is the simplest. A coarse product, with particle size less than 200 µm, attained a significant reduction in ash content to 22.4 percent but with low CMR of 17.7 percent, whereas elimination of the fine component alone, with particle size less than 10 µm, only reduced the ash content to 34.8 percent but with significantly higher CMR of 83.0 percent.

EGS of the ROM ultrafine with the MGS was found to only reduce the ash content by 7 percentage points to 31.8 percent but with high CMR of 95.8 percent. Processing after sieve bend recovery of the > 200 µm fraction and elimination of the < 10 µm fines significantly improved the product ash content to 25.7 percent. The combination of sieve bend classification and EGS attained CMR of 90.1 percent with ash content of 25.0 percent.

Froth flotation of the ultrafine sample yielded a product with the lowest ash content of 19.5 percent along with high CMR of 92.3 percent. Combustion of this product should generate the least nonproductive thermal plant emissions. As the flotation time can be varied to produce a product with different ash content but reduced CMR, it is the most versatile of the processes. Although it is probably the process with the highest operating cost, product value would also be greatest provided the flotability of the feed is consistent, a condition that many coal preparation plants may not be able to maintain.

The combination of sieve bend recovery of the > 200 µm fraction and EGS processing of the remaining > 10 µm fraction is the most complicated but yielded the next best product with 25.1 percent ash content and 90.1 percent CMR. This process is not subject to variations in feed properties, such as clay content and coal hydrophobicity. It also has the benefit of eliminating most, if not all, of any pyrite or marcasite present. Combustion of this product should generate a third less nonproductive thermal plant emissions than the unprocessed coal.

The high moisture contents of all the ultrafine coal products are largely associated with the intergranular porosity of the coal product. A theoretical, ash-free product would still have 16.25 percent moisture content. It is suggested that air blow drying within filter presses be considered. Although this will not improve the product calorific value per kilogram, it would decrease transportation costs, but avoiding losses as dust would require an enclosed product storage facility. Alternatively, the product could be blended with coarser coal products, but this would not reduce the risk of explosions.

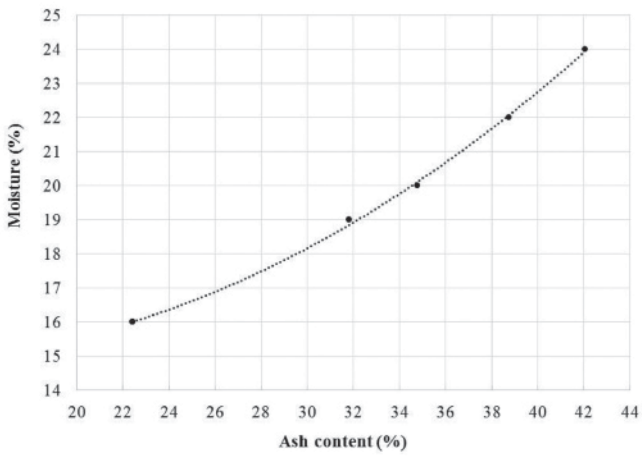

Figure 8 — Humidity of filter-pressed ultrafine coal products in relation to the ash content.

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