DRY COAL CLEANING USING THE FGX SEPARATOR

R. Q. Honaker[1], M. Saracoglu[1], E. Thompson[1], R. Bratton[2], G. H. Luttrell[2] and V. Richardson[3]
[1]*University of Kentucky, Department of Mining Engineering*
[2]*Virginia Tech, Department of Mining & Minerals Engineering*
[3]*Eriez Manufacturing*

ABSTRACT

The potential of dry cleaning coal of nearly all ranks using a pneumatic table concentrator commercially known as the FGX separator has been evaluated as part of an on-going investigation. The evaluation has been performed at several sites throughout the U. S. where coal is extracted from surface open cast, highwall and underground operations as well as from coarse reject. The treated coals varied in feed ash content (i.e., 7-70%). Regardless of the mineral matter type, pure rock removal into the reject stream was achieved in all applications with little coal loss. Field data obtained when treating 2 x ¼-in ROM bituminous coal indicate that 70-90% of the >2.0 RD rock can be rejected. As a result, a clean product having acceptable market quality was generated from several coal sources including both lignite and bituminous coals. This paper provides an overview of data from recent field testing of the dry air table technology and discusses the potential implementation strategy for the various sites evaluated.

INTRODUCTION

Interest in dry coal cleaning has increased significantly in recent years mainly due to a need to clean lignite and sub-bituminous coals in the western and Gulf Coast regions of the U.S. Expectations are that requirements for cleaning Powder River Basin coal will increase in the near future due to changing geological conditions that include the presence of intrusions in some of the major coal seams. An additional application is the removal of high density rock from run-of-mine coal in the Central Appalachia coalfields prior to shipment to a processing facility. The economics of mining the thin coals seams in this region requires the extraction of a large amount of out-of-seam material which commonly has resulted in low plant yield values in the range of 35% - 50%. Honaker *et al.* (2006) also showed that the treatment of low-ash run-of-mine coal to remove the small amount of rock using a dry separator prior to blending with washed coal has significant economical benefits.

Dry particle separators have a long history of application in the U.S. coal industry. According to Arnold *et al.* (1991), the amount of coal processed in the U.S. through dry cleaning plants reached a peak in 1965 at 25.4 million tons. The largest dry-based cleaning plant located in Pennsylvania processed 1400 tph of minus 3/4-inch coal using a total of 14 units. The last complete dry cleaning plant operating in Kentucky was closed in the late 1980's. Reasons for the decline in dry coal production to less than 4 million tons annually by 1990 include increased run-of-mine moisture levels that resulted from dust suppression requirements and the demand for higher quality, compliance coal which required efficient, low density separations.

Several of the dry, density-based separators used throughout the twentieth century were developed in the period from 1910 to 1930 (Osborne, 1988). The technologies incorporated the same basic principle mechanisms that are commonly employed in wet cleaning separators including: 1) dense medium separations, 2) pulsated air jigging, 3) riffled table concentration and 4) air fluidized coal launders whereby the coal is fluidized into the top layers of a particle bed and subsequently skimmed off.

The effective top size particle for most of the separators was around 2 inches and the effective size ratio for which good separation was achieved was between 2:1 and 4:1. It is noted that this effective particle size range is much smaller than most wet, density based separators. The reported probable error (E_p) values vary due to the particle size ranges treated. For example, within a small particle size range of 4:1, the E_p values ranged from 0.15-0.25 whereas a 50:1 ratio provided *Ep* values around 0.30. These values indicate that the air-based systems are much inferior in separation efficiency as compared to wet coarse coal cleaning units. However, dry coal cleaning devices typically have lower capitol and operating costs, no waste water treatment and impoundment requirements, lower product moisture values and less permitting requirements. If a high density separation provides the desired effect on coal quality, dry cleaning separators are an attractive option.

Several processing technologies used during the peak years of dry coal preparation have been recently modified and successfully commercialized. The Allair Jig, for example, is a modification of the Stump Jig technology and is commercially represented by Allminerals Ltd. (Kelly and Snoby, 2002). The unit has been successfully applied in several applications within and outside the U.S. for coal cleaning (Weinstein and Snoby, 2007). Chinese researchers and manufacturers have applied basic fundamentals including computational fluid dynamics to the redesign of dry particle separators including those employing dense medium and tabling principles. The FGX Separator is an example of a Chinese dry, density-based separation technology that has several hundred commercial installations (Lu *et al.*, 2003, Li and Yang, 2006). A mobile pilot scale unit of the FGX Separator has been evaluated for the cleaning of run-of-mine and waste coal sources of all ranks throughout the U.S. This publication will present and discuss the separation performances achieved on the U. S. applications.

EXPERIMENTAL

Process Description

The FGX dry cleaning system employs the separation principles of an autogenous medium and a table concentrator as shown in Figure 1. The feed is introduced into a surge bend from which the underflow is controlled using an electro-magnetic feeder. The separation process generates three product steams, i.e., clean coal product, middlings, and tailing streams. Two dust collection systems are employed to clean the recycled air and to remove the dust from air being emitted into the atmosphere. The separating compartment consists of a deck, vibrator, air chamber and hanging mechanism. A centrifugal fan provides air that passes through holes on the deck surface at a rate sufficient to transport and fluidize the particles. Riffles located on the deck direct material toward the back plate. The deck width is reduced from the feed end to the final refuse discharge end. Upon introduction of feed coal into the separation chamber, a particle bed of a certain thickness is formed on top of the deck. The presence of about 10-20% minus 1/4-inch material in the feed is needed to develop a fluidized autogenous medium particle bed. Low density particles (such as coal) form the upper layer of particles that are collected along the front length of the table. The upward fluidization velocity is insufficient to fluidize the high density particles (such as rock) and thus they maintain contact with the table surface where both vibration and the continuous influx of new feed material move the material to the narrow end of the table where the final refuse is collected

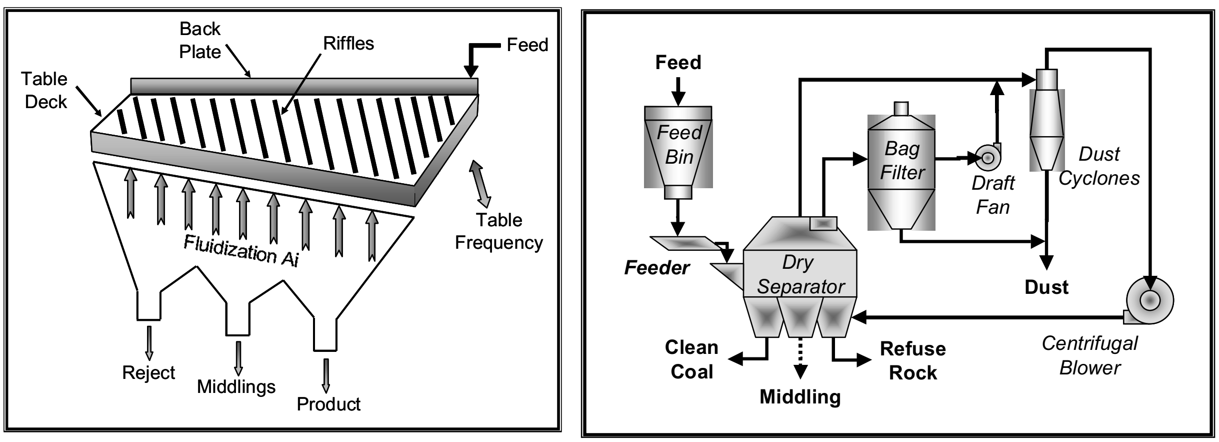

Figure 1
Schematics showing the basic operation of the FGX Separator unit.

Test Program Description

A 5 tph pilot scale FGX Separator unit was used at the various test sites. With the exception of the coarse reject material, a three-level statistically-designed test program was performed on each run-of-mine coal to determine if the magnitude of the parametric effects vary as a function of coal rank and the amount of reject material in the feed. Four operating variables were evaluated at the first test site including fluidization air rate, table frequency, longitudinal table slope and cross-table slope. The total number of tests was 29. After the first test program, the cross-table slope was kept at a constant value thereby resulting in a reduction in the number of tests to 15. By varying the parameter values systematically, the optimum test performances and the corresponding conditions were identified.

The feed at each site was pre-screened using an inclined vibrating screen having ¼-inch apertures. The purposes were to ensure that the separation process was not affected by the presence of an excessive amount of fine material and to minimize the negative effects of feed moisture. Since the minus 1/4-inch material is required to form a fluidized medium, the screening process was operated in a manner that allowed a portion of the fine fraction to report to the FGX unit.

The sampling program used two different approaches. The first approach involved collecting representative samples of the product, middling and tailing streams with established splitter positions. The second approach utilized a specially designed collection device that divided the material exiting the edge of the table into six different splits. The splits were 16 inches apart, which allowed the quality of the products to be evaluated as a function of table length.

RESULTS AND DISCUSSION

Utah Bituminous Coal

The initial test program was performed on bituminous run-of-mine coal at an operation in Utah. The objective of the test program was to produce a clean coal product that was sufficient in quality to meet specifications for a steam coal contract. The required operating conditions to meet the objective vary from coal-to-coal due to the unique physical characteristics of the coal including the particle size and density distributions, particle shape of the coal and reject material and the quantity of high density rock in the feed. As such, the values of four critical operating parameter values were varied over 29 tests according to a three-level statistical design. The two splitter positions were maintained at pre-determined settings throughout the program and timed samples of the feed, product, middling and tailing streams were collected from each test.

The average feed ash content was reduced from 18.21% to 10.76% in the clean coal over 29 tests with the mass yield to the product stream averaging 76.8% of the total feed weight. Since product grade was the most important response parameter in meeting the objective, the assays and weights of the middling samples were combined with those from the tailing samples to form the total reject material which explains the lower than expected yield. The corresponding average reduction in total sulfur content was 1.61% to 1.49%. From the individual tests, product ash and total sulfur contents realized from the FGX Separator were as low as 9.55% and 1.39%, respectively, with a mass product yield of 75.20%. The average ash and total sulfur contents in the tailings stream was 72.70% and 2.67%, respectively. Tailing ash content values greater than 80% were realized from several tests.

Efficient separation performances were achieved from tests that reduced the ash content to values around 11% as shown by the comparison with feed washability data in Figure 2. This observation reflects the ability of the FGX unit to effectively remove the high density rock while minimizing the loss of coal. However, using the unit to achieve low density separations leads to relatively low efficiencies as indicated in this case by the difference between the washability and FGX yield for product ash values below 11%.

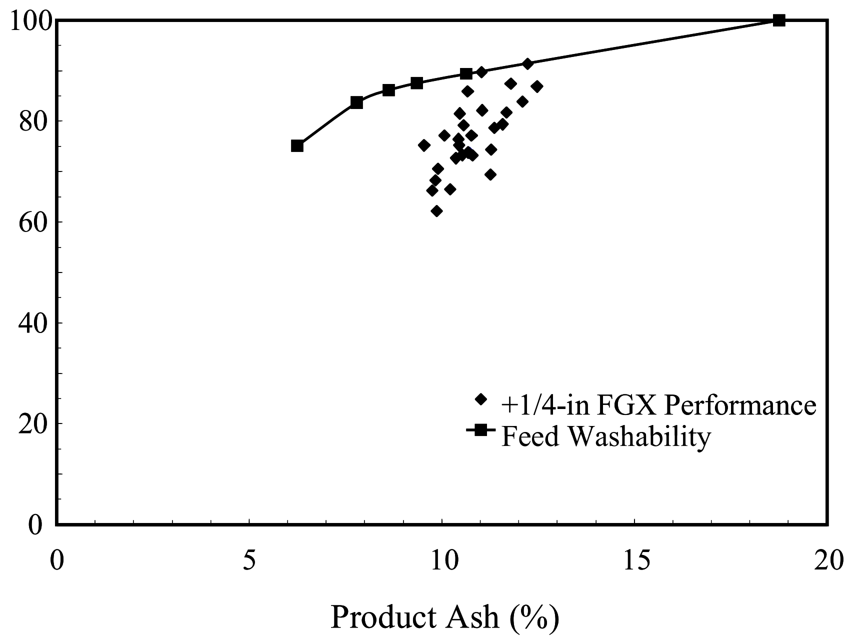

Figure 2
FGX ash reduction performance on Utah bituminous run-of-mine coal.

A test was performed to investigate the effect of feed ash content by blending tailings material with the run-of-mine coal. The result was an elevated feed ash content of 28.38% versus the 16.32% level present in the feed of a comparison test performed under the same operating conditions. As shown in Table 1, the FGX Separator was able to effectively reject the increased amount of rock with little effect on the product quality and energy recovery.

Test No.	Ash Content (%)			Total Sulfur Content (%)			Mass Yield (%)	Energy Recovery (%)
	Feed	Product	Tailings	Feed	Product	Tailings		
1	28.38	11.36	81.77	1.58	1.41	3.83	62.1	76.8
2	16.62	10.49	68.16	1.55	1.42	5.93	70.4	75.5

Table 1
Effect of Feed Ash Content on FGX Performance

Process efficiency was evaluated by developing partition curves from washability data obtained for samples collected from a FGX test that reduced the ash content from 16.44% to 9.87% while recovering 82.9% of the feed coal. The experimental data produced two partition curves: 1) curve 1 represents the separation between the product and middlings streams (i.e., middling and tailings material combined as total reject) and 2) curve 2 reflective of the separation between the middling and tailings stream (i.e., product and middlings combined as total FGX clean coal product). Using the data from the two partition curves, a linear analysis was performed to assess the performance if the middlings stream was recycled to the FGX feed stream to recover the misplaced coal and reject the high-density rock (Figure 2). From the analysis, the overall partition number R_o for the separation with middlings recycle can be quantified using:

$$R_o = \frac{P}{F} = \frac{R_1}{R_1 + (1 - R_1)(1 - R_2)} \quad [1]$$

where R_1 and R_2 are the partition numbers for the product-middling separation and the middlings-tailings separation, respectively.

The FGX Separator partition curves support the results in Figure 1 in that the separator has the ability to reject a significant amount of high-density rock with minimal loss of coal. As shown in Figure 3, combining the middlings and product streams resulted in a high-density separation (ρ_{50}) of 2.26 R.D and rejection of about 70% of the high-density rock. By routing the middlings stream to the tailings stream, the ρ_{50} was reduced to 1.87 RD and the amount of high-density rock rejected increased to about 88%. However, a significant amount of 1.60 float material was lost to the reject due to the misplacement of the particles in the middlings stream. The process efficiency values of both options were approximately equal with a E_p value of 0.25. By recycling the middlings stream, both the recovery of 1.6 float and rejection of high-density rock were improved. The separation density was approximately 2.0 RD and the E_p value was 0.17.

Central Appalachia Coal

The removal of rock from Central Appalachia run-of-mine coal prior to loading and hauling to a preparation plant has the potential of significantly improving energy efficiency and reducing operating costs. Tests were performed on a bituminous run-of mine coal at a mining operation located in Virginia. The goal was to maximize rock rejection while minimizing coal loss.

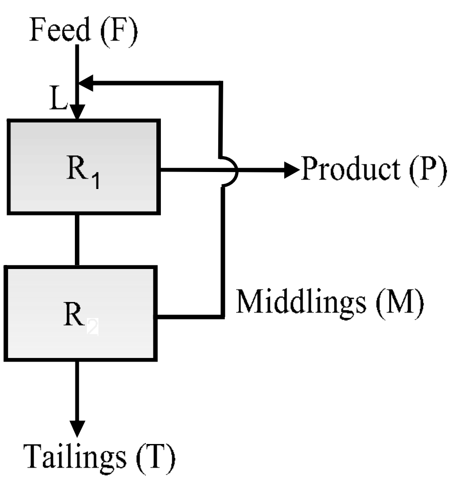

Figure 2
Linear Analysis of Middling Recycle

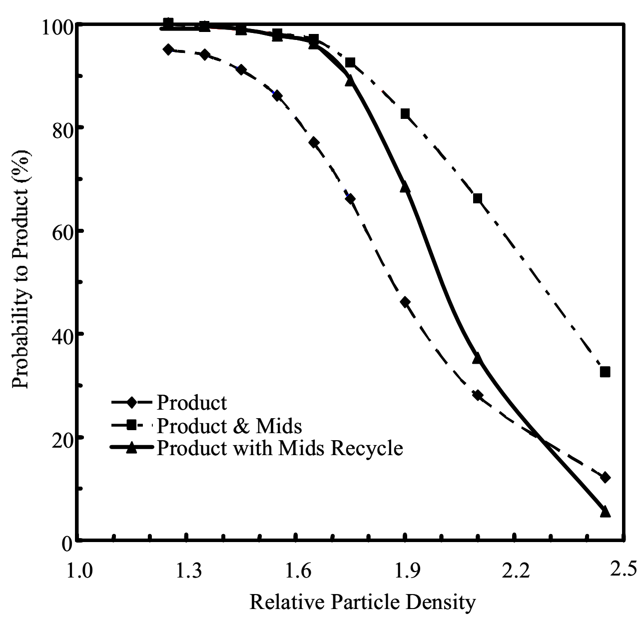

Figure 3
Partition curves generated from FGX Separator Performances.

Operating parameter values were varied in each test according to a statistically-designed test program. The feed ash content averaged 49.27%.

As shown in Table 2, the ash reductions achieved by the FGX Separator was significant with product ash content values less than 15% being realized in several tests. Given the program objectives, the FGX unit produced ash contents greater than 87% ash in the tailings stream in all tests indicating the ability to reject high-density rock without the loss of coal. Also, a few test conditions yielded ash contents in the middlings material exceeding 80% with greater than 50% mass yield to the product stream.

Under the conditions of Test No. 2, high-density rock removed from the run-of-mine material resulted in approximately 33.5% of the feed material being rejected. To assess the potential economical benefit, consider a 450 tph operation that operates 6000 hours annually and transports the run-of-mine coal 15 miles to a wet processing plant. The average transportation cost in the Central Appalachia region is $0.30/ton*mile. By rejecting 33.5% of the feed material, the annual reduction in operating cost is about $4 million.

Test No.	Feed Ash (%)	Product Ash (%)	Middlings Ash (%)	Reject Ash (%)	Yield (%)
1	50.00	19.46	83 .38	89.03	53.5
2	51.69	34.05	87.08	89.51	66.5
3	54.88	29.09	78.19	87.75	48.4
4	48.27	25.75	80.42	89.92	55.9
5	51.58	25.97	78.41	91.37	58.8
6	46.70	17.87	68.21	88.34	44.5
7	50.84	16.84	55.11	87.30	34.6
8	54.33	15.53	62.70	87.02	34.0
9	38.05	29.02	82.04	89.80	58.5
10	50.18	19.69	78.26	90.09	51.1
11	45.88	34.50	86.30	91.09	66.7
12	49.93	12.88	72.51	90.13	46.1
13	47.14	13.96	57.02	88.90	37.3
14	51.69	14.78	71.90	87.95	43.4
15	47.87	12.63	73.30	89.38	42.9
Aver.	49.27	21.47	74.32	89.17	49.5

Table 2
Separation Performance achieved on a Run-of-Mine Virginia Bituminous Coal.

From tests performed on a bituminous run-of-mine coal in West Virginia, an analysis of the reject material from the FGX unit indicated that the dry separator removed high-density material containing less than 1.32% coal that floats at a density of 1.6 RD (Table 3). The reject represented about 36% of the run-of-coal coal. Based on the typical operation, the reduction in operating cost is $4.37 million annually. The loss of coal resulting from rejecting the high-density material is 13,122 tons annually. Assuming a $40/ton coal value, the loss of coal has an annual value of $524,000. The operating cost of the FGX unit has been estimated at $0.50/ton which, for the example, equates to $1.35 million. Thus, the net profit gain from removing the high density rock is about $2.5 million annually. If the middling and tailing streams are combined, greater amounts of rock can be reject at a cost of more than double the amount of 1.6 RD float.

Test Number	Middlings & Reject Combined		Reject Only	
	% of Feed	% Float 1.6 RD	% of Feed	% Float 1.6 RD
1	50.7	3.71	35.9	1.51
2	49.5	2.82	33	0.90
3	55.1	3.72	36.6	1.32
4	52.4	2.73	36.4	0.78

Table 3
FGX Reject Analysis from the Treatment of a West Virginia Bituminous Coal.

Powder River Basin Coal

The processing of Powder River Basin coal typically involves simple crushing and loading. However, during the extraction process, out-of-seam rock contaminates some of the coal. The contaminated coal, typically referred to as ‘rib’ coal, is normally kept in the pit as fill material. At one coal operation, rib coal amounts to 1 to 10 millions tons annually which represents a significant loss in potential revenue. Tests were performed to evaluate the feasibility of the FGX Separator to reject the out-of-seam rock and produce a marketable clean coal product.

The evaluation involved using the same parametric test program used for the eastern bituminous coal. The coal was screened to achieve a nominal 2 x ¼-inch particle size fraction to feed the dry separator. During the PRB parametric studies, the table products were sampled in five splits to provide mass and quality distributions of the material exiting the table. Product and reject streams were calculated as the combination of Splits 1 through 3 and Splits 4 through 6, respectively. Split 4 averaged about 47% ash from all 15 tests which indicates the presence of misplaced coal that could be recovered. Removing Split 4 from the tailings material resulted in a reject stream containing an average of 83.74% ash-bearing material. However, the goal of the study was to simply determine if a high quality coal could be produced from the current waste material and a corresponding estimate of yield.

The variation in the separation performances listed in Table 4 is indicative of the parametric values changes that were studied during the test program. The FGX Separator proved the ability to achieve a product quality sufficient for meeting market requirements. The ash content was reduced on average from 20.79% to 8.40% while recovering 59.1% of the current waste material. In some tests, the mass yield approached 90% while achieving product ash contents below 10%.

Test No.	Feed Ash (%)	Product Ash (%)	Reject Ash (%)	Yield (%)	Energy Recovery (%)	Ash Reduction (%)
1	18.86	7.05	71.28	82.11	94.07	62.62
2	15.61	6.77	62.92	78.00	86.17	56.65
3	23.83	9.63	58.45	75.45	89.52	59.58
4	21.25	7.84	61.36	68.71	80.42	63.13
5	21.98	7.67	69.60	82.83	98.03	65.13
6	19.68	10.69	81.93	91.66	100.00	45.69
7	19.60	8.49	79.12	81.10	92.30	56.66
8	13.91	7.41	70.02	82.40	88.62	46.76
9	22.83	9.01	74.38	86.74	100.00	60.54
10	23.60	9.26	69.42	78.38	93.08	60.74
11	21.02	9.06	81.71	89.08	100.00	56.92
12	19.59	7.99	64.69	74.74	85.52	59.22
13	23.03	7.27	52.07	74.22	89.41	68.44
14	23.33	9.29	70.87	69.24	81.92	60.20
15	23.72	8.57	63.12	69.71	83.56	63.88
Average	20.79	8.40	68.73	78.96	90.84	59.08

Table 4
FGX Separator Performances from the Treatment of PRB Sub-Bituminous coal.

Gulf Coast Lignite Coal

The objectives of the test program performed on Gulf Coast lignite coal were to assess the feasibility of the FGX Separator to:

1) Reduce the total sulfur content of coal that is not marketable as a direct ship product;
2) Decrease the mercury content;
3) Improve the heating value.

The three goals are listed in the order of priority.

The feed coal was relatively low in ash content but high in total sulfur. A statistically-designed experimental program was performed to quantify the parametric efforts and to obtain optimum separation performance levels. The splitter positions were used in the test program to generate product, middling and tailing streams. The average separation performance achieved from the 17 test program provided a significant sulfur reduction from 1.91% to 1.23%. The sulfur reduction was due to the presence of large coal pyrite particles. Ash reduction was limited due to the low amounts of high density rock in the feed (i.e., 6.59% to 4.86% ash). As such, the improvement in the heating value was minimal (7710 BTU/lb to 7817 BTU/lb). Despite the low feed ash, the average mass yield to the product stream was 79%. The yield values were reflective of misplaced coal in the middlings stream which was combined with the tailings stream in the analysis. The splitter position is an operating parameter that can be changed to achieve the desired product grade while minimizing coal loss.

The most significant impact provided by the FGX Separator was the reduction in sulfur and mercury contents as shown in Figure 4. The average total sulfur reduction was 34.8%, which equates to an average SO_2 (lb/M-Btu) reduction of 35.8%. Although the feed sulfur content varied, the FGX Separator provided a consistent product SO_2 content of 3.2 lbs/M-Btu. It is generally known that the mercury content in coal is generally associated with the pyritic minerals. This well established observation is apparent in the Gulf Coast lignite coal as indicated by a large HG reduction of 54.4%. Although mercury content varied significantly throughout the testing program, a Hg content less than 10 lbs/T-Btu was generally achieved from the material in product stream.

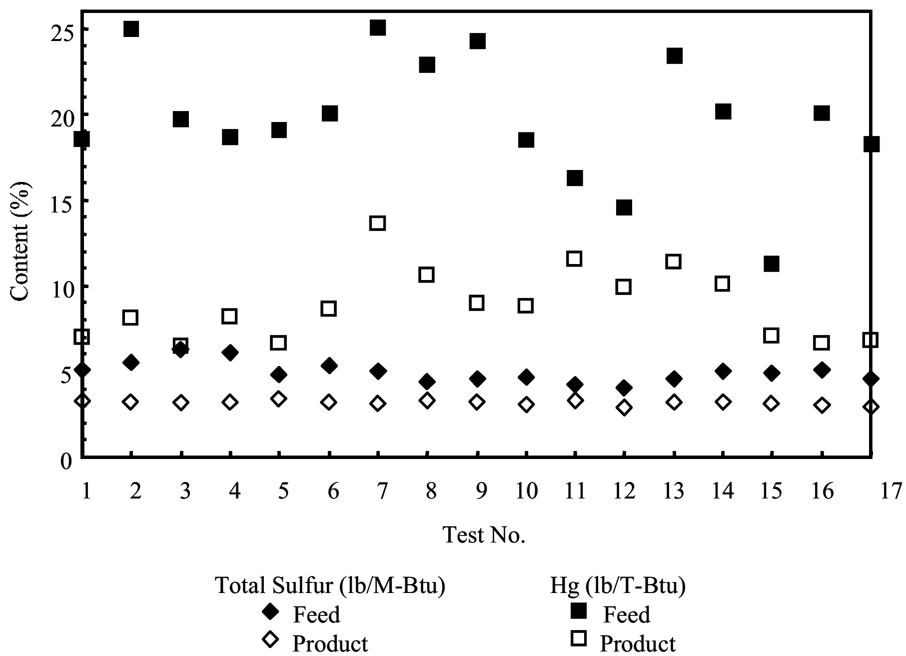

Figure 4
FGX Separator Sulfur and Mercury Reduction Performances for Gulf Coast Lignite Coal.

Coarse Gob Coal

Coarse reject generated from previous preparation practices often contains a significant amount of high quality coal, especially at operations that existed prior to the 1980's. In the Central Appalachia region, decades of metallurgical quality coal was produced by attempting low density separations using the best available technology. The result was a high concentration of coal in the coarse reject that may contain moderate energy value as reflected by their relative particle densities (1.4-1.8 RD) and, in some cases, a significant amount of high energy coal as a result of process inefficiencies.

The 5 tph FGX unit was installed at an eastern Kentucky coarse reject site with the goal of achieving a clean bituminous coal product that could be marketed as steam coal. Objectives included maximizing quality while minimizing coal loss. A washability analysis of the plus 1/4-inch fraction of a coarse reject sample collected at the site revealed that 45.3% of the material had a relative density less than 1.8 and a heating value of 10499 Btu/lb. The overall ash content and heating value of the material was 60.25% and 5408 Btu/lb, respectively.

A series of seven tests were performed over a range of operating parameter values to determine the optimum operating conditions. An important observation from the test results was that the longitudinal slope of the table must be maintained low when producing a high coal quality from feed coal containing a large amount of rock. Table 5 details the separation performance achieved along the length of the table under the optimum operating conditions. A separation between the 4^{th} and 5^{th} split resulted in a clean coal product containing nearly 10000 Btu/lb while recovering 44.5% of the total feed coal. Similar to the performance achieved on the previous coal sources, split 6 was comprised of mostly high density as indicated by an ash content of 81.53% and represents a significant amount of the total feed (i.e., 39.5%).

Table Split Number	Incremental Values			Cumulative Values		
	Weight (%)	Ash (%)	Heating (btu/lb)	Weight (%)	Ash (%)	Heating (btu/lb)
1	12.19	31.32	10216	12.19	31.32	10216
2	17.91	34.83	9656	30.09	33.41	9883
3	10.96	33.28	9843	41.05	33.37	9872
4	3.44	29.57	10496	44.49	33.08	9920
5	16.01	49.24	7081	60.50	37.36	9169
6	39.50	81.53	1849	100.00	54.80	6278
	100.00	54.80	6278			

Table 5
FGX Separation Performance on Kentucky coarse gob.

A second coarse reject material was evaluated at a site in Virginia. The feed contained 77.6% plus ¼-inch material and 55.54% ash. The amount of 1.8 RD float material in the plus ¼-inch fraction of the feed was 46.4%. A total of three tests were performed and Splits 5 and 6 were combined to obtain an appropriate amount of sample to analyze. The FGX Separator provided a significant upgrading as indicated by a decrease in the ash content from 55.54% to 31.84% when combining Splits 1 and 2 thereby resulting in a cumulative mass yield of 44.4% (Table 6). However, it is apparent that improvement in ash reduction is possible based on the amount of 1.8 RD sink in the two splits. The amount of 1.8 RD float material in Split 3 indicates potential to recover a significantly greater amount of coal by recycling the stream to the feed of the separator. The excellent deshaling capability of the FGX unit is demonstrated by the combined ash content of 84.40% in Splits 4 and 5 which represents 37.79% of the total feed.

Table Split Number	Incremental Values			Cumulative Values	
	Weight (%)	Ash (%)	% 1.8 RD Float	Weight (%)	Ash (%)
1	21.96	29.89	84.63	21.96	29.89
2	22.43	33.74	77.66	44.39	31.84
3	17.82	53.38	49.09	62.21	38.01
4	17.26	80.32	8.32	79.47	47.20
5	20.53	87.83	1.02	100.00	55.54
Total	100.00	55.54	46.40		

Table 6
FGX Separation Performance on Virginia coarse gob.

Based on washability data and the results presented in Table 6, it is feasible that the operating set points of the FGX unit could be altered to produce clean coal with a near 20% ash content or a second FGX Separator could be employed as a cleaner unit for the same purpose. An alternative scenario is to use the dry cleaner to reject as much rock as possible and transport the product to a wet cleaning plant to achieve the desired product grade.

SUMMARY AND CONCLUSIONS

The FGX Separator provides a dry, density-based separation that utilizes the combined separating principles of an autogenous fluidized bed and a table concentrator. A dry particle separation has been evaluated at several mining operations across the U.S. for the treatment of run-of-mine coal and coarse coal reject of all ranks. The objectives of the test programs at each site varied and included 1) the production of clean coal having qualities that meet contract specifications and 2) maximization of the amount of high-density rock rejected prior to transportation and processing. A 5 tph pilot-scale unit of the FGX Separator was installed and a detailed parametric study performed at each site to ensure that optimum performances were realized for each coal.

The FGX Separator provides a relatively efficient separation at high separation density values of around 1.8 RD to 2.2 RD. The typical probable error (E_p) value achieved was 0.25. However, if the middling stream is recycled to the feed stream, the process efficiency can be significantly improved as indicated by a reduction in the E_p value to 0.17. Partition curves clearly indicate that the FGX unit has the ability to reject at least 70% of the high density rock in a run-of-mine coal without loss of coal and the need to recycle the middlings stream. The impact was realized when treating Central Appalachia bituminous coal that contained significant amounts of high-density material. From run-of-mine coal, the FGX Separator removed 36% of the total which contained only about 1.3% coal that floated at 1.60 RD. Coarse reject material that was generated from decades of wet preparation plant production was also affectively treated to recover coal with a heating value around 10,000 Btu/lb.

For coals containing little or no material having a density between 1.6 RD and 2.0 RD, the FGX Separator has the ability to produce a product that meets utility contract specifications. For sub-bituminous coal from the Powder River Basin, the ash content was reduced from about 20.79% to 8.40% on average over a test program of 15 tests which involved systematic variations in the critical operating values. Similar results were obtained for bituminous run-of-mine coal at a mining operation in Utah. The dry air table separator also reduced the total sulfur and mercury contents of Gulf Coast lignite by 35% and 54%, respectively.

ACKNOWLEDGEMENTS

The research discussed in this publication was funded in part by the U.S. Department of Energy through the Mining Industry of the Future program (DE-FC26-05NT42501). The authors greatly appreciate the assistance provided by the personnel of the mining companies at each of the test sites.

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