FINAL TECHNICAL REPORT

Project Title:

DEVELOPMENT OF AN ADVANCED DESHALING TECHNOLOGY TO IMPROVE THE ENERGY EFFICIENCY OF COAL HANDLING, PROCESSING, AND UTILIZATION OPERATIONS

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Applicant: University of Kentucky Research Foundation
Principal Investigator: Rick Q. Honaker
Department of Mining Engineering, University of Kentucky, Lexington, Kentucky 40506-0107
Phone: (859) 257-1108; Fax: (859) 323-1962; e-mail: rhonaker@engr.uky.edu

Co-Principal Investigator: Gerald H. Luttrell
Department of Mining & Minerals Engineering, Virginia Tech
Blacksburg, Virginia 24060

Project Team

University of Kentucky
Virginia Tech
Peabody Energy
Massey Energy
Eriez Manufacturing

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EXECUTIVE SUMMARY

The concept of using a dry, density-based separator to achieve efficient, near-face rock removal, commonly referred to as deshaling, was evaluated in several applications across the U.S.. Varying amounts of high-density rock exist in most run-of-mine feed. In the central Appalachian coalfields, a rock content exceeding 50% in the feed to a preparation plant is commonplace due to high amounts of out-of-seam dilution made necessary by extracting coal from thin seams. In the western U.S, an increase in out-of-seam dilution and environmental regulations associated with combustion emissions have resulted in a need to clean low rank coals and dry cleaning may be the only option.

A 5 ton/hr mobile deshaling unit incorporating a density-based, air-table technology commercially known as the FGX Separator has been evaluated at mine sites located within the states of Utah, Wyoming, Texas, West Virginia, Virginia, Pennsylvania and Kentucky. The FGX technology utilizes table riffling principles with air as the medium. Air enters through the table and creates a fluidized bed of particles comprised of mostly fine, high density particles. The high density particle bed lifts the low-density coal particles to the top of the bed. The low-density coal moves toward the front of the table due to mass action and the downward slope of the table. The high-density particles settle through the fluidized particle bed and, upon making contact with the table, moves toward the back of the table with the assistance of table vibration. As a result, the low-density coal particles exit the front of the table closest to the feed whereas the high-density, high-ash content particles leave on the side and front of the table located at the farthest from the feed entry.

At each test site, the run-of-mine feed was either directly fed to the FGX unit or pre-screened to remove the majority of the -6mm material. The surface moisture of the feed must be maintained below 9%. Pre-screening is required when the surface moisture of the feed coal exceeds the maximum limit. However, the content of -6mm in the feed to the FGX separator should be maintained between 10% and 20% to ensure an adequate fluidized bed.

A parametric evaluation was conducted using a 3-level experimental design at each test site to identify the optimum separation performance and parameter values. The test data was used to develop empirical expressions that describe the response variables (i.e., mass yield and product ash content) as a function of the operating parameter values. From this process, it was established that table frequency and longitudinal slope are the most critical factors in controlling both mass yield and clean coal ash while the cross table slope was the least significant. Fan blower frequency is a critical parameter that controls mass yield. Although the splitter positions between product and middling streams and the middling and tailing streams were held constant during the tests, a separate evaluation indicated that performance is sensitive to splitter position within certain lengths of the table and insensitive in others.

For a Utah bituminous coal, the FGX separator provided clean coal ash contents that ranged from a low of 8.57% to a high of 12.48% from a feed coal containing around 17% ash. From the 29 tests involved in the statistically designed test program, the average clean coal ash content was 10.76% while the tailings ash content averaged around 72%. One of the best separation performances achieved an ash reduction from 17.36% to 10.67% while recovering 85.9% of the

total feed mass, which equated to an ash rejection value of around 47%. The total sulfur content was typically decreased from 1.61% to 1.49%. These performances were quantified by blending the middlings stream with the clean coal product.

At a second Utah site, coal sources from three different bituminous coal seams were treated by the FGX deshaling unit. Three parameter values were varied based on the results obtained from Site No. 1 to obtain the optimum results shown in Table E-1. Approximately 9 tests were performed on each coal source. The average ash content reductions were: Glenwal (= 25.6% to 8.6%), Pinnacle (=17.3% to 9.0%) and Westridge (=20.6% to 7.5%). Under optimum conditions, nearly 70% of the high-density rock was rejected while recovering approximately 100% of the 1.60 float material.

In the Powder River Basin, a small portion of the extracted coal is mistakenly diluted with out-of-seam rock. Since coal cleaning is not currently practiced, the diluted coal containing 20%-30% ash is left in the pit as fill material, thereby representing a lost resource. A FGX test program conducted on the high ash sub-bituminous coal revealed the ability to produce clean coal containing 7% - 8% ash on a dry basis (5% - 6% on an as-received basis) with 62% recovery. The product grade meets typical end user contract specifications for PRB coal.

In Texas, lignite is used to generate a majority of the electric production and, in some locations, the coal contains elevated amounts of sulfur in the form of pyrite. A series of tests revealed that the FGX separator has the ability of reducing the total sulfur content by over 40% and the mercury content by as much as 67%. Energy recovery was nearly 90%. As a result of these findings, the construction of a full-scale 600 tph dry cleaning facility was commissioned and production started in 2008.

Several coal sources were tested in the eastern U.S. with the objective of maximizing rock rejection while ensuring nearly 100% energy recovery. For a Virginia mining operation, the FGX unit rejected 33.5% of the feed coal that contained 88% ash bearing material. Considering a 15 mile haul from the mine to the preparation plant at a cost of \$0.30/ton*mile, a 450 ton/hr operation could save \$4 million annually in transportation costs. At a West Virginia mine, the coal is transported by rail haulage to a wet coal cleaning facility. FGX tests produced a reject containing 0.78% of 1.6RD float material representing 36.4% of the total feed. An economic analysis considered the savings in reduced transportation as well as the costs of the lost coal and operating the dry cleaner. The findings indicate the potential to gain \$4.6 million annually from a 500 tph operation. A 17% reduction in energy use was estimated by employing dry separation technology at the mine site, which also reduces the amount of impact land and reduces the size of slurry impoundments.

Coal recovery from coarse coal waste generated from past mining operations was also evaluated at two sites. In general, the FGX separator recovered +6mm coal containing between 30% and 35% ash. The heating value was upgraded from around 6000 Btu/lb to 10,000 Btu/lb while recovering 45% of the feed material in the +6mm size fraction. The quality of the material recovered from coarse gob has sufficient value to be used as blend coal in the utility market.

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1.0 BACKGROUND

Deshaling is the process of removing high density rock from coal. In contrast to the coal cleaning in traditional preparation plants, the separation density is higher with a typical target of 2.0 relative density or greater. An additional objective is to place the deshaling unit as close to the extraction face as possible to reduce transportation and maintenance costs. The concept was the focus of an extensive study in the 1980's which led to the development of the wet, density-based Humboldt ROMJIG (Sanders et al., 2000; Sanders and Ziaja, 2003). Current interest is to identify an efficient and cost-effective dry cleaning technology for the purpose of achieving the deshaling objective.

Recent studies have indicated significant technical and economical benefits for deshaling coals in a number of different situations (Luttrell et al., 1996; Honaker et al., 2004), i.e.,

i. Removing high density rock from a steam coal that is not being processed through a preparation plant in an effort to improve heating value.

ii. Reducing rock content from run-of-mine coal prior to loading and transportation. In the Central Appalachia coalfields in the U.S., coal is being extracted with 60% - 70% reject due to out of seam dilution and transported 20 – 30 miles to the preparation plant. This situation is an ideal application for deshaling.

iii. Eliminating rock from coal that is not treated and blended with a processed coal to achieve a product having the required quality. The studies have shown that the use of deshaling on the untreated coal to remove one ton of rock will allow the recovery of three additional tons of middling material currently rejected during the processing of the treated coal.

The economics of deshaling for steam coal applications are understood on the basis of an improved heating value and the fact that utilities pay on the basis of \$/MMBtu rather than \$/ton. Consider a situation where a coal with a heating value of 12500 Btu/lb is worth \$50/ton. The total heating value for the coal is 25 MMBtu (= 1 ton x 2000 lb/ton x 12,500 Btu/lb). As such, the monetary value of the coal is \$2 per MMBtu (= \$50/25 MMBtu). Thus, improving the heating value through deshaling provides the potential to significantly improve revenue.

As a result of eliminating the transportation, handling and storage of material having no heating value, it is estimated that an annual energy savings of nearly 270 trillion btu units can be realized using deshaling units at U. S. coal mining operation.

1.1 Deshaling Technologies

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-in 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-in 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 provides 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 Stomp Jig technology and is commercially represented by Alminerals Ltd. (Kelly and Snoby, 2002). The unit has been successful 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).

1.2 FGX Separator

The FGX dry cleaning system employs the separation principles of an autogenous medium and a table concentrator. As shown in Figure 1, the feed to the system is introduced into a surge bend from which the underflow is controlled using an electro-magnetic feeder. The separation process generates three products, i.e., deshaled 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 (Figure 2a). 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 the feed coal into the separation chamber, a particle bed of certain thickness is formed on the deck. The particles near the bottom of the bed directly contact the vibrating deck and move from the discharge baffle plate toward the back plate under the effect of the vibration-induced inertia force. Upon striking the back plate, the particles move upward and inward toward the discharge side of the table (Figure 2b). Light particles are lifted up the back plate at a higher elevation than the dense particles before turning inward toward the discharge point. As such, light particles create the upper layer of particles that are collected along the length of the table. Particles of sufficient density are able to settle through the autogenous medium formed due to the fluidized bed of particles and report back to the deck surface. These heavy particles are forced by both vibration and the continuous influx of new feed material to transport in a helical transport pattern toward the narrowing end of the table where the final refuse is collected.

Performance data for the FGX separator is currently limited to tests on Chinese coals and a few pilot-scale tests on U.S. coals. However, the separation data collected to date indicates that this system offers an attractive and cost-effective alternative to traditional coal preparation processes, particularly for green-field sites where coal cleaning operations are being utilized for the first time (e.g., India). The data obtained from studies conducted in China indicate that the unit has the potential to provide an effective separation for particles as coarse as 80 mm (3 inches) to a lower size limit of around 3 mm (0.1 inches). The operational data also indicate that the process is relatively insensitive to surface moisture up to a value of about 7-10% by weight. As shown in Table 1, the FGX unit has the ability to provide a relatively high separation density (RD_{50}) of around 2.0 RD while achieving probable error (Ep) values that range from 0.15 to 0.25 (Lu et al., 2003). This level of performance provides high organic efficiencies approaching 97%. The capital cost for a 250 t/hr unit was reported to be less than one fourth that of a traditional preparation plant design with operating costs below US$0.30 per tonne.

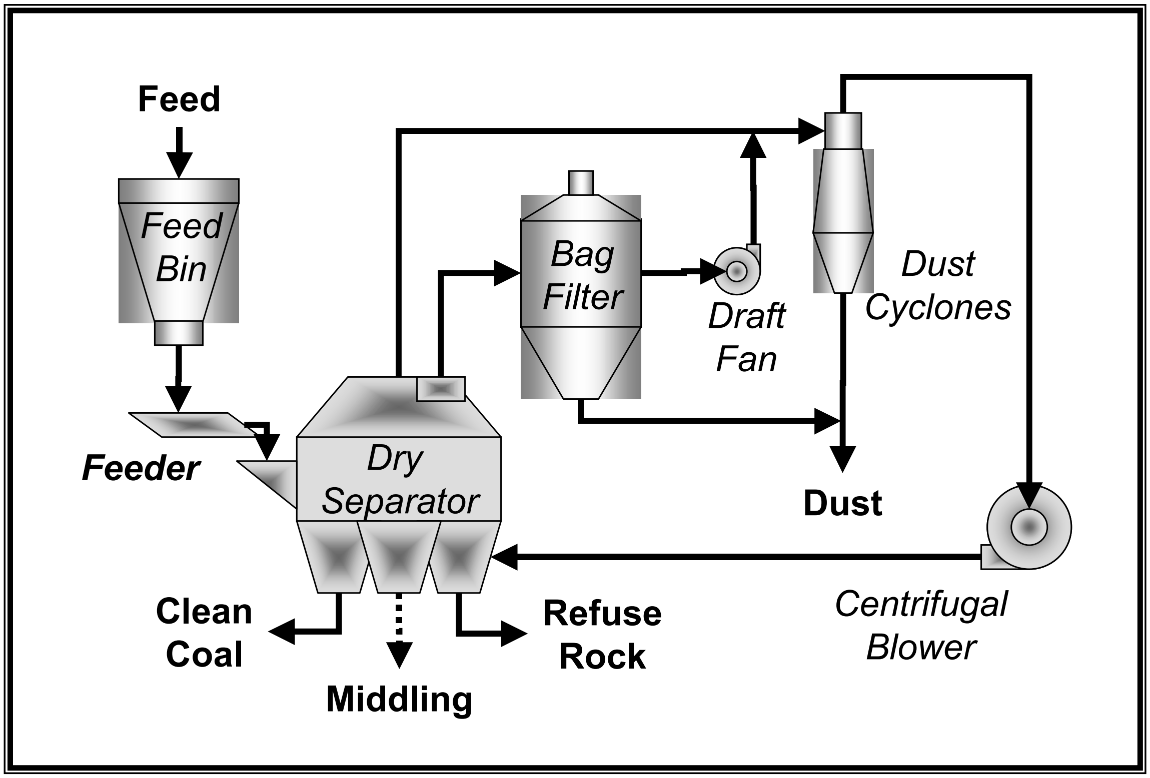


Figure 1. Simplified process flowsheet for the FGX air table separator system.

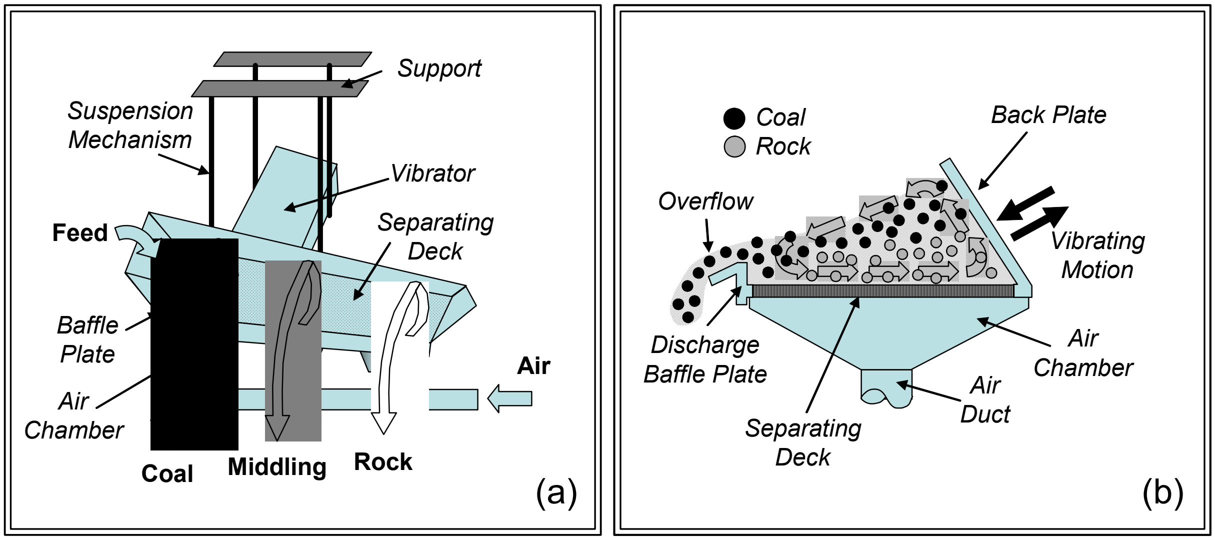


Figure 2. Illustrations of the FGX unit showing (a) the separation chamber and (b) helical particle motion and separation mechanism.

Table 1. Performance data for the FGX separator for different Chinese coals (50 x 6 mm).

Efficiency Parameter	Mine A	Mine B	Mine C
Separation Density (RD_{50})	2.12	1.98	1.82
Probable Error (E_P)	0.23	0.15	0.25
Organic Efficiency (%)	96.96	96.65	---

2.0 PROJECT GOALS AND OBJECTIVES

The goal of the project was to significantly enhance the energy efficiency and economics of transporting, processing and utilizing coal by employing a novel, dry deshaling technology near the extraction point of surface mining operations. The pilot-scale FGX unit was mobilized and tested at numerous sites across the U.S. for the treatment of all ranks of coal. Test programs were conducted in Utah (bituminous coal), Texas (lignite coal), Wyoming (sub-bituminous coal), Virginia (bituminous coal), West Virginia (bituminous coal), Pennsylvania (anthracite) and Kentucky (bituminous coal). Test programs were also conducted on coarse gob material to assess the potential of using the FGX separator to recover coal from waste generated from previous coal processing activities.

Success in various degrees was realized at each test site. For example, the treatment of Powder River Basin coal focused on the recovery of coal from material that is currently left in the mine face area due to dilution with out of seam material. A product ash content of around 8.4% on a dry basis was obtained from the waste material using the FGX unit at a recovery of 90%. The treatment of Gulf Coast lignite resulted in 40% total sulfur reduction and 60% mercury reduction. This performance resulted in a decision to install a full-scale dry coal cleaning facility using the FGX separator to clean the coarse particle size fraction. In the eastern U.S., several test programs demonstrated the ability of the FGX separator to remove 30% to 50% of the run-of-mine coal. The rejected material contained more than 70% ash with little heating value. By removing the material, the total amount of material requiring transportation to a coal cleaning plant, processed and subsequently transported to an above-ground storage facility was significantly reduced.

The project objectives and accomplishments are compared in Table 2. Most of the project objectives were successfully achieved. However, the total project funding received was approximately 60% of the awarded amount. As a result, project tasks focused on developing an on-line process efficiency system for dry cleaning and expanding the particle size range that can be cleaned by the FGX unit was not addressed. The project accomplishments exceeded the total funding received.

Table 2. Project objectives and accomplishments.

Project Objectives		Project Accomplishments
1. Optimize the operating and physical parameters to provide efficient high density separations while achieving 100% total energy recovery.		1. A 5-tph dry cleaning unit was evaluated at several mining operations across the U.S. using statistically designed test program. The results were used to identify the optimum separation performance and the set of parameter values.
2. A significant enhancement of energy efficiency due to reducing the need to haul, process and store pure rock		2. The dry cleaning unit was found to have the ability to reject 30% - 50% material containing little to no heating value. As a result, significant energy savings will be obtained from the reduction of material transported, processed and stored. Energy savings are estimated to be 9 million kwh/year which represents a 17% reduction for a 2.95 million ton operation.
3. Improvement in mining economics through the replacement of pure rock in the product with a threefold weight increase in the recovery of middling particles		3. Significant rejections of pure rock was obtained in several test programs conducted on all ranks of coal across the U.S.. By installing a units at the mine site, economic savings can be realized from reduced transportation, handling and processing. For a typical operation, the economic savings was estimated to be $4.6 million annually.
4. Reduction in the environmental impact of mining and utilizing coal		4. In nearly every case except for the Powder River Basin and Gulf Coast coals, 30% - 50% of the feed was rejected by the dry cleaner as high ash material. This material can be kept at the mine and used as fill material rather than placed into above-land storage facilities. Dry cleaning is the only option for low rank coals and the FGX unit demonstrated the ability to significantly reduce ash, total sulfur and mercury. A full-scale FGX unit was recently installed for this purpose for the cleaning of lignite.
5. Employ the use of tracers for on-line efficiency evaluations in a dry density-based separations		5. Not accomplished due to reduced funding.
6. Increase the effective particle size range that can be treated.		6. Not accomplished due to reduced funding.

3.0 GENERAL EXPERIMENTAL METHODOLOGY

A 5 tph pilot scale FGX Separator unit utilizing a 1 m^2 air table was used at the various test sites. The feed to the unit was supplied directly from the mine or pre-screened to remove the -6mm material from the feed prior to treatment. Underground coal sources required pre-screening due to the relatively large amount of fines and the amount of surface water present due to dust suppression activities. Feed coal was fed to the bin shown in Figure 3 by a conveyor or front-end loader. Feed from the feed bin was controlled using a vibratory feeder and transferred via a conveyor belt to a hopper that feeds an internal screw conveyor. The screw conveyor feeds an internal hopper subsequently feeds the back right corner of the table (Figure 4).

Figure 3. On-site test set-up using the 5 tph FGX pilot-scale air table.

Upon entry of the feed onto the table deck, the upward flow of air creates a fluidized-bed of fine reject which causes the light coal particles to migrate to the top of the particle bed. The coal moves toward the right front part of the table due to the downward slope of the table (e.g., typical slope is 8^{O} downward from the back of the table to the front). The high-density particles ride on the table surface which is vibrated at a preset frequency. The vibration drives the high-density particles to the back of the table where the particles are forced by mass action to travel toward the left side of the table.

The particles that overflow the front of the table are directed into product, middling or tailing bins by splitters that are adjusted to achieve a clean coal product and a high-ash content tailings. The material in each of the three bins is transferred by conveyor away from the FGX unit.

Figure 4. Deck (1 m^2) of the FGX air table.

With the exception of tests performed on 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 28. 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 sampling program used two different approaches. The first approach involved collecting representative samples from 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 18 inches apart which allowed the quality of the material exiting the table to be evaluated as a function of table length.

4.0 PROJECT ACCOMPLISHMENTS

4.1 Western U.S. Coal Test Progam

4.1.1 Utah Bituminous Coal

The deshaling system was transported and setup at two mining operations in Utah that treated bituminous coal. A representative sample of the feed from the first site was analyzed to determine the particle size-by-size and density-by-density weight and quality distributions. As shown in Table 3, the majority of the ash-forming components existed in the +1/4-in material. As such, the feed was prescreened using a ¼-inch screen and the overflow directed to the feed bin of the FGX unit. The washability data indicated potential to achieve a significant reduction in the ash content by achieving a high density separation in the FGX unit. A product containing less than 10% ash can be realized as a result of a density separation at a cutpoint of 2.0.

Table 3. Characterization data obtained from analysis of the run-of-mine bituminous coal at Mine Site No. 1.

Size Fraction (mm)	Particle Size Analysis			Specific Gravity Fraction	Washability Analysis		
	Weight (%)	Ash (%)	Total Sulfur (%)		Weight (%)	Ash (%)	Total Sulfur (%)
50 x 25	12.85	31.62	1.63	1.4 Float	75.06	6.25	1.85
25 x 12.7	34.71	19.90	1.69	1.4 x 1.6	8.61	21.32	1.63
12.7 x 6.3	41.97	15.62	1.67	1.6 x 1.8	2.42	37.12	2.85
- 6.3	10.47	11.81	4.19	1.8 x 2.0	1.44	53.24	3.79
				2.0 x 2.2	1.84	71.40	3.11
				2.2 Sink	10.63	87.10	2.12
Total	100.00	18.76	1.93	Total	100.00	18.76	1.93

The second site in Utah was at an Andalex mining operation that produced coal from three different coal seams. Five different coal sources were evaluated. Each coal source was screened to obtain 50 x 9mm material to feed the FGX unit.

Parameter Evaluation & Optimization

At test site No. 1, the test program conducted on the FGX pilot-scale unit was performed using a Box-Behnken test design to evaluate and optimize the values of four operating parameters that were identified as being the most critical. The amplitude of the table was maintained at 8 mm while the air valve supplying air to the table was set at the full open position. The parameters and parameters values used in each test are provided in Table 4. Feed rate was maintained at a level of around 5.6 tons/hr (5.0 metric tons/hr). The tests were conducted in continuous mode with no recycling of the middling stream. Mass yield values were determined based on the middlings stream being combined with the tailings stream to represent the total reject.

Table 4. Parameters and value levels evaluated in the Box-Behnken test program.

Operating Parameter	Parameter Value Levels		
	Low	Middle	High
Air Blower (hz)	50	55	60
Table Frequency (hz)	40	45	50
Cross-Table Slope (degrees)	8.0	8.5	9.0
Longitudinal Slope (degrees)	0.5	1.0	1.5

At site No. 2 (Andalex), the test program conducted on the FGX pilot-scale unit was performed by changing three parameters that were identified as being the most critical based on the earlier findings at test site No. 1. The tests were conducted in continuous mode with no recycling of the middling stream. The parameters and parameters values used in each test are provided in Table 5. Feed rate was maintained at a level of around 5.6 tons/hr (5.0 metric tons/hr) while the values of the other operating parameters were kept at the levels provided in Table 6. All analytical data are presented on an air-dried basis in this report.

Table 5. Parameters and parameter values evaluated in the FGX test program (Site 2, Andalex).

Test Number	Air Blower (hz.)	Table Frequency (hz.)	Cross Table Slope (degree)	Longitudinal Slope (degree)
1	55	45	8.5	1.0
2	55	40	8.5	1.5
3	55	40	8.5	0.5
4	60	45	8.5	1.5
5	60	45	8.5	0.5
6	60	40	8.5	1.0
7	50	45	8.5	1.5
8	60	40	8.5	0.5

Table 6. Parameter values maintained constant during FGX test program (Site 2, Andalex).

Parameter	Position A	Position B	Position C
Air Valve Setting	Full Open	Full Open	Full Open
Front Gate Position (mm)	32 - 45	7 - 32	0 - 18
Splitter Position	1	3	
Amplitude (mm)	8		
Reject Door	Closed		

Results and Discussion

Separation Performance (Utah Site 1): The average ash reduction achieved during the test program by the FGX unit was from 18.21% to 10.76% while recovering 76.8% of the total feed weight. The total sulfur content was decreased from 1.61% to 1.49%. This equates to ash and total sulfur rejection values of 53.9% and 29.0% on average, respectively. As a result, the average heating value of the coal was upgraded from 11513 Btu/lb to 12691 btu/lb. Product ash and total sulfur contents realized from the FGX unit were as low as 9.55% and 1.39%, respectively, with minimal effect on overall product yield.

The average ash content in the tailings stream was 72.70% and values greater than 80% were realized from several tests. Also, sulfur was found to be effectively concentrated into the tailings stream as indicated by an average sulfur content of 2.67%.

The separation performances on the basis of ash reduction are compared with +1/4-inch washability data in Figure 5. A high level of efficiency was achieved when producing a clean coal products containing greater than 10.5% ash. As the product ash decreased beyond this value, organic efficiency (=actual recovery/washability recovery) decreased significantly. The main reason for this trend is that the middlings and tailings stream data were combined as total FGX refuse for yield and recovery calculations. The middling stream material contained 29.62% ash on average and represented about 14% of the total feed flow rate. This data indicates that a significant amount of clean coal and pure rock remains in the middling stream and thus needs to be recycled to the primary feed stream to recover the misplaced coal. If one assumes that clean coal containing 10% ash product and a tailings material containing 75% ash could be recovered from the middlings stream represented by the average ash content from the 29 tests, secondary treatment of the middlings has the potential to provide an increase in yield of nearly 10 absolute percentage points above the average performance, which equates to a mass yield of 86.8%.

The results from four of the best performances achieved over a range in product ash contents are summarized in Table 7. The results show:

1. The FGX has the ability to reduce ash content to values below 12% while maintaining a high level of recovery.
2. Rock is effectively rejected into the tailings stream without losing coal as indicated by the high tailings ash.
3. The middlings stream requires retreatment to recover misplaced, low-density coal.

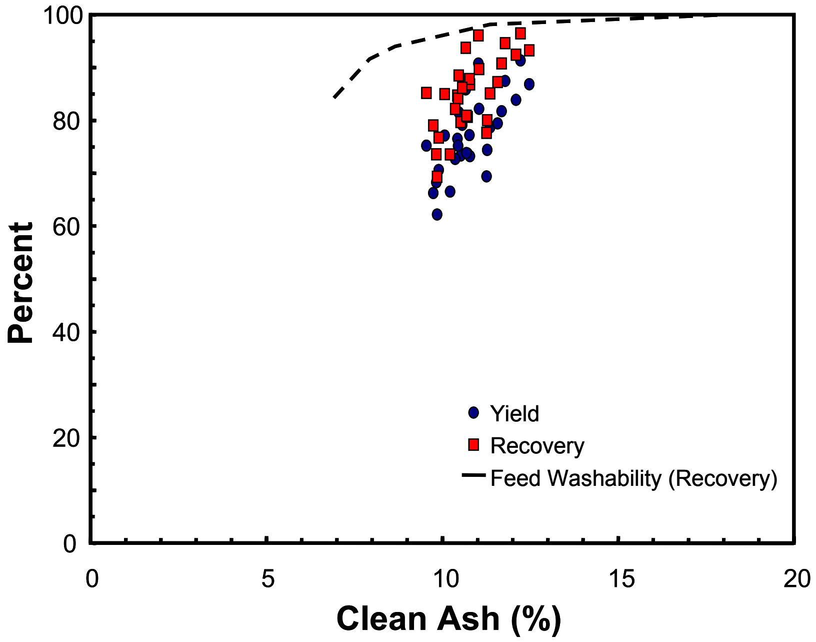


Figure 5. Comparison of the FGX separation performances with +1/4-in washability data.

Table 7. Optimum separation performances achieved from the 29 parameter evaluation tests.

Test	Feed Ash (%)	Product Ash (%)	Middlings Ash (%)	Tailings Ash (%)	Product Yield (%)
1	19.10	9.55	23.56	70.24	75.2
2	17.36	10.67	47.24	77.67	85.9
3	15.62	11.03	59.02	80.42	90.8
4	16.38	12.23	58.23	80.63	91.4

Parametric Evaluation (Site 1): The data from the statistically-designed test program were used to develop empirical models describing mass yield and clean coal ash content as a function of the operating parameter values. Both models successfully passed the model and 'lack-of-fit' tests that are associated with ANOVA analyses. The R^2 and adjusted R^2 values for the yield model were 0.848 and 0.806, respectively, which indicates a reasonably good fit to the experimental results within the parameter value ranges tested. The ash model is adequate with corresponding R^2 values of 0.710 and 0.613.

The form of the models is:

$$Y = A_1 + A_2(ABF) + A_3(TF) + A_4(CTS) + A_5(LS) + A_6(ABF^2) + ... + A_i(CTS \times LS) \qquad [1]$$

where Y is the response variable (either yield or product ash), A_i the corresponding coefficients, *ABF* the air blower frequency, *TF* the table frequency, *CTS* the cross-table slope and *LS* the longitudinal slope. Based on a significance test of each parameter in the model, the model for each response parameter was reduced to include only the significant terms. The coefficients for each model term are provided in Table 8. All possible parameter interactions (e.g., TF x CTS) were evaluated. The most important parameters for both yield and clean coal ash were table frequency and longitudinal slope. The cross table slope had the least effect and was borderline significant for both yield and product ash. Unexpectedly, air blower frequency had no statistically significant effect on product ash content.

Within the range of operating parameter values tested, the optimum separation performance and corresponding conditions as defined by maximizing yield and minimizing clean coal ash content are provided in Table 9. The fact that the optimum conditions correspond to the maximum air blower frequency and longitudinal slope tested in this program indicates that potential exists for improved performance outside the upper value limits.

Table 8. Yield and clean coal ash model coefficients.

Model Terms	Mass Yield Coefficients A_i	Clean Coal Ash Coefficients A_i
Intercept	-367.95	237.12
ABF	0.57	---
TF	-18.40	-2.20
CTS	198.29	-40.81
LS	10.66	-12.08
TF^2	0.19	0.02
CTS^2	-11.58	2.34
LS^2	---	-1.48
CTS x *LS*	---	1.89

Table 9. Optimum operating conditions and separation performance.

Air Blower (hz.)	Table Frequency (hz.)	Cross Table Slope (degree)	Log. Slope (degree)	Clean Coal Ash (%)	Mass Yield (%)
60	42.5	8.3	1.5	10.19	86.13

The separation performance can also be controlled by the splitter positions which are positioned to separate the product, middlings and tailings streams. A study was performed to quantify the distribution of the ash-bearing material across the length of the deck as shown in Figure 6. From Table 10, it is clear that the ash content and wt% of the coal exiting the FGX deck varies significantly throughout the entire length of the table. The data suggests that relatively clean coal reports in positions 1 through 3 while high density reject material reports to positions 5 and 6 under the given loading conditions. The material in position 4 is comprised of mixed-phase particles as well as misplaced low-density and high-density material. Figure 4 cumulates the mass yield reporting to the product stream and the ash content from the clean coal end to the tailings end. Under the conditions described above, a clean coal product containing about 10% ash can be produced while recovering 78% of the total feed mass. The mass yield can be significantly increased if the middlings fraction is recycled to the feed stream for re-processing.

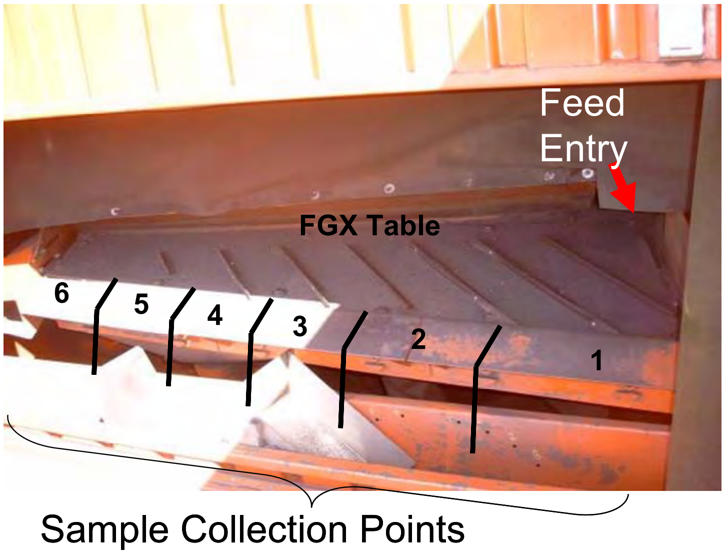
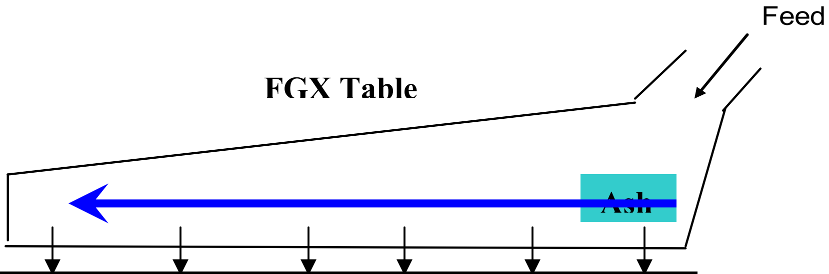


Figure 6. The sample collection points through out the deck of the FGX separator.



Sample No.	6	5	4	3	2	1
Weight %	1.60	11.66	8.33	11.66	30.00	36.66
Ash %	79.41	80.46	58.33	15.68	10.57	9.53
sulfur %	0.36	0.62	0.46	0.61	0.56	0.47
Btu	1212	850	5527	12371	13111	13290

Table 10. Distribution of ash-bearing material across the length of the air table.

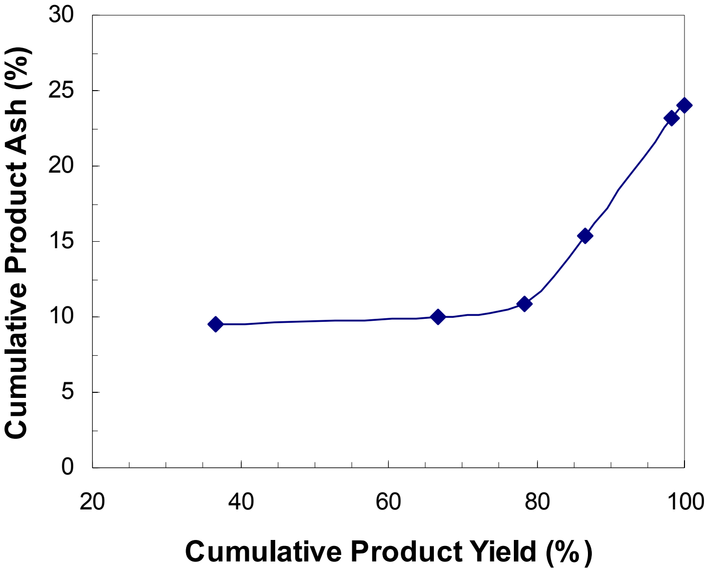


Figure 7. Separation performance as a function of splitter position.

Separation Performance (Utah Site 2): Westridge Coal Seam: The Westridge coal proved to be a challenging sample for the FGX separator because of its low feed ash content. Over the entire test program, the average ash reduction achieved by the FGX unit was from 9.92% to 6.02% while recovering 57.22% of the total feed weight (Table 11). This equates to ash rejection values of 64.03% on average. The overall total sulfur content (1.27%) did not decrease because in this sample, sulfur exists mainly in organic form. As a result, the average heating value of the coal was upgraded from 13443 Btu/lb to 14063 Btu/lb. The optimal energy recovery realized from the FGX unit was 69% which corresponds to a mass yield of 65.5% and a product ash content of 5.94%. The low yield and energy recovery values are a result of a significant amount of high quality coal that reported to the middlings stream.

Table 11. Separation performance data achieved for the Westridge coal sample; air-dried basis.

Test No.	Ash Content (%)				Total Sulfur (%)				Yield (%)	Energy Recovery (%)
	Feed	Clean Coal	Mids	Tails	Feed	Clean Coal	Mids	Tails		
1	12.93	5.84	11.72	54.19	1.41	1.24	1.65	2.23	56.3	61.5
2	11.37	7.47	9.00	50.96	1.23	1.30	1.35	1.74	58.3	61.2
3	10.58	5.94	8.89	43.09	1.25	1.22	1.29	1.44	65.5	69.0
4	7.96	5.79	8.35	26.22	1.33	1.23	1.27	2.02	62.0	63.3
5	10.36	4.71	9.36	32.56	1.14	1.19	1.33	1.35	54.3	57.7
6	7.12	5.45	6.92	18.18	1.25	1.25	1.23	1.29	55.4	56.8
7	11.71	6.80	9.06	29.60	1.23	1.23	1.25	1.60	52.4	55.5
8	7.35	6.12	8.41	31.83	1.28	1.24	1.24	1.68	53.4	53.8
9	15.02	7.10	9.31	40.86	1.18	1.28	1.28	1.44	38.4	42.1

Glenwal Coal: For the Glenwal feed coal, the average ash reduction achieved by the FGX unit was from 25.57% to 8.56% while recovering 56% of the total feed weight (Table 12). This equates to an average ash rejection value of 80.28%. The average ash content in the tailings stream was 75.52% and values greater than 80% were realized from several tests. As a result, the mean heating value of the coal was upgraded from 10764 Btu/lb to 13470 Btu/lb.

Table 12. Separation performance data of the Glenwal coal sample; air-dried basis.

Test No.	Ash Content (%)				Total Sulfur (%)				Yield (%)	Energy Recovery (%)
	Feed	Clean Coal	Mids	Tails	Feed	Clean Coal	Mids	Tails		
13*	22.40	9.04	27.74	72.49	0.54	0.63	0.59	0.40	47.3	56.5
14	34.27	9.59	47.67	82.28	0.43	0.58	0.59	0.21	68.3	97.7
15	34.28	8.76	24.23	76.77	0.47	0.58	0.64	0.28	42.9	62.2
16	29.17	7.40	49.71	83.17	0.54	0.54	0.45	0.21	65.2	88.6
17	23.97	8.54	33.69	78.78	1.33	0.59	0.53	0.30	59.1	69.0
18	20.20	8.13	20.83	58.49	0.54	0.59	0.54	0.41	38.2	44.7
19	22.82	9.04	28.65	75.96	0.58	0.58	0.54	0.33	60.6	73.3
20	22.46	8.30	16.95	67.93	0.95	0.59	0.73	0.46	48.9	59.0
21	17.38	8.71	34.87	80.75	0.57	0.58	0.57	0.30	65.1	72.0

* The sample was wet when treated in the FGX

Pinnacle Coal: The Pinnacle ROM coal was processed first in the Accelerator and screened to provide sample for the FGX separator. The Accelerator is a technology that selectively break rock away from coal and produces a -2-inch product which was further treated by the FGX separator. The overall ash reduction achieved by the FGX unit for the Pinnacle tests was from 17.22% to 9.01% while recovering 55% of the total feed weight (Table 13). This equates to an average ash rejection value of 71%. The ash content in the tailings stream averaged 60.95% with values exceeding 70% achieved from several tests. The average heating value of the coal was upgraded from 11889 Btu/lb to 12988 Btu/lb. The optimum separation performance resulted in a clean coal product having 8.42% ash with an energy recovery of 76.6% (Test No. 22).

Table 13. Separation performance data achieved while treating Pinnacle coal sample; air-dried basis.

Test No.	Ash Content (%)				Total Sulfur (%)				Yield (%)	Energy Recovery (%)
	Feed	Clean Coal	Mids	Tails	Feed	Clean Coal	Mids	Tails		
22	16.30	8.42	26.80	74.40	0.46	0.48	0.44	0.30	69.0	76.6
23	16.83	9.17	11.00	54.99	0.46	0.48	0.49	0.38	50.2	60.6
24	22.08	9.19	21.04	70.65	0.43	0.50	0.45	0.30	68.0	68.5
25	19.03	9.26	18.60	71.89	0.47	0.49	0.46	0.34	62.2	70.2
26	16.03	9.18	14.26	51.53	0.47	0.47	0.47	0.38	43.2	46.7
27	17.45	9.44	12.01	58.36	0.49	0.49	0.48	0.39	52.4	55.4
28	15.52	8.73	11.63	49.30	0.48	0.48	0.50	0.38	39.6	43.2
29	14.49	8.72	12.37	56.46	0.49	0.49	0.48	0.33	56.1	59.8

Westridge Coal: The Westridge coal is characterized as having relatively high ash and sulfur contents. Over the entire test program, the ash reduction achieved by the FGX unit was from 20.56% to 7.53% while recovering 55.68% of the total feed weight (Table 14). The total sulfur content was decreased from 1.68% to 1.48%. This equates to ash and total sulfur rejection values of 78.51% and 50.74% on average, respectively. As a result, the average heating value of the coal was upgraded from 11677 Btu/lb to 13765 Btu/lb. The minimum product ash and total sulfur contents were 6.44% and 1.41%, respectively.

Table 14. Separation performance data achieved while treating Westridge high ash and sulfur coal sample; air-dried basis.

Test No.	Ash Content (%)				Total Sulfur (%)				Yield (%)	Energy Recovery (%)
	Feed	Clean Coal	Mids	Tails	Feed	Clean Coal	Mids	Tails		
31	27.71	7.01	15.20	48.36	1.72	1.50	1.69	2.37	26.7	34.8
32	18.27	7.77	17.26	58.38	1.69	1.48	1.73	2.06	47.5	54.2
33	19.40	7.44	16.03	55.59	1.63	1.51	1.57	2.08	44.0	50.9
34	17.83	8.19	28.51	72.06	1.70	1.57	1.93	2.10	71.5	81.2
35	23.32	7.60	26.17	72.26	1.72	1.42	1.80	2.25	67.0	82.5
36	18.93	6.44	16.19	57.51	1.60	1.49	1.63	2.34	48.8	56.6
37	21.77	8.10	39.87	73.41	1.68	1.49	1.98	2.09	73.6	88.2
38	17.27	7.65	22.78	67.06	1.66	1.41	1.84	2.45	66.5	74.6

Process Efficiency Evaluation

The efficiency of the separation achieved under the operating conditions that resulted in the ash reductions in Test 2 listed in Table 11 was evaluated by performing particle size-by-size washability analyses on representative samples from the feed and output streams. The data obtained from the middlings stream analysis were combined with those from the product streams to generate the partition curves in Figure 8. The significant finding is that 70% of the high density rock can be rejection while recovering greater than 5% of the 1.60 float material and 100% of the 1.5 float material.

The partition curves resulting from the middlings material being sent to the tailings stream indicates an overall relative separation density of around 1.87 with a corresponding probable error value of 0.24 (Figure 9). The total rock rejection was increased to about 85%. However, there was a significant amount of coal by-pass to the reject stream. The differences between the partition curves in Figures 4 and 5 are indicative of the amount of coal existing in the middlings stream, which further emphasizes the need to re-process the middlings stream to maximize recovery. As expected, separation density increases and process efficiency depreciates significantly with a reduction in particle size. In fact, the efficiency achieved on the -1/4-in material was poor; however, when the middlings stream is recovered to the product stream, 30% of the rock in the fine fraction can be rejected while recovering nearly 100% of the 1.6 float fraction (Figure 8).

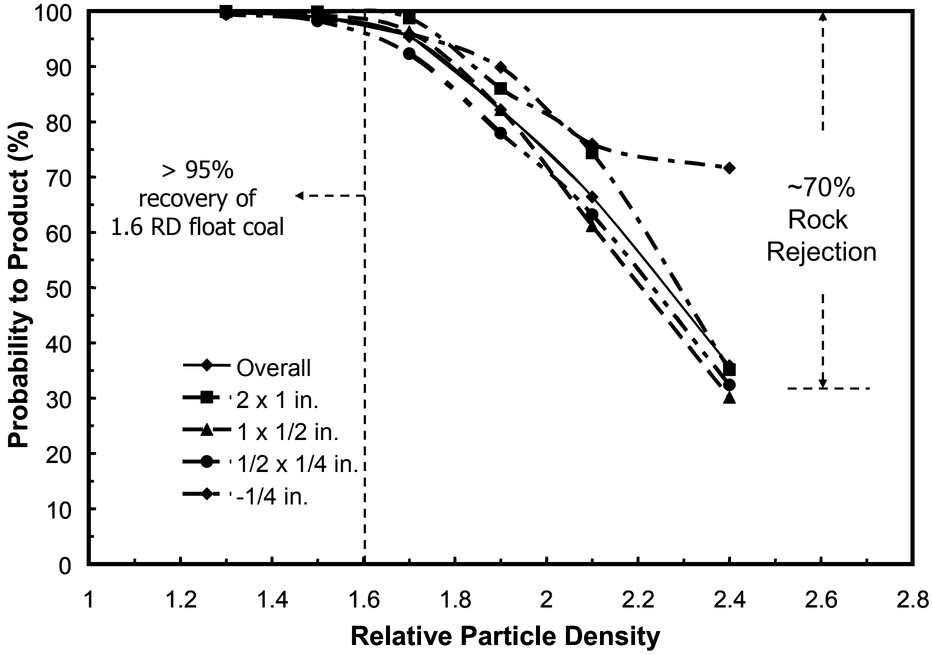


Figure 8. Particle size-by-size efficiency achieved by combining the product and middlings streams.

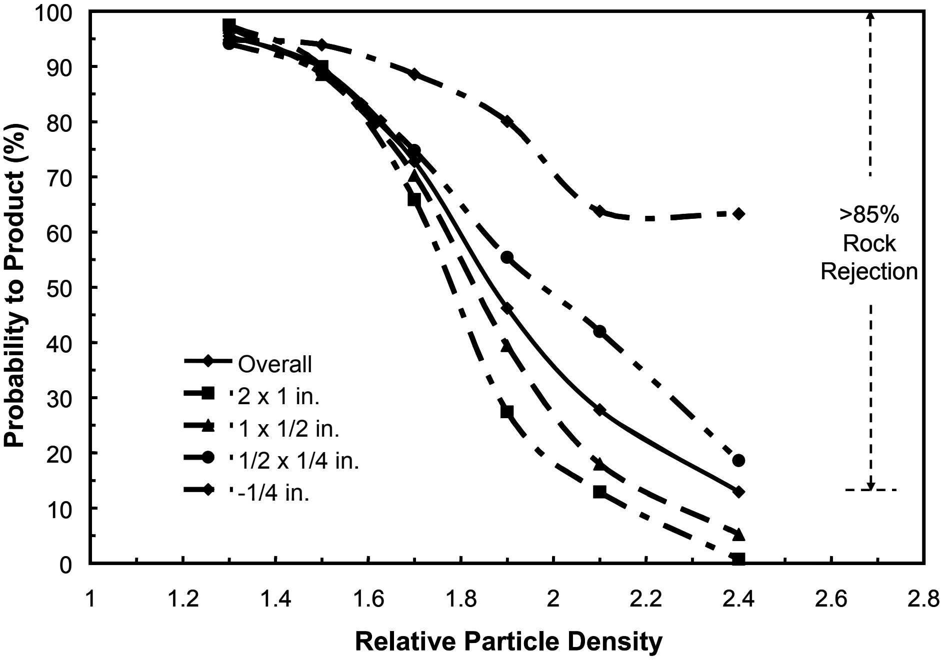


Figure 9. Particle size-by-size efficiency achieved by combining middlings and tailings streams.

Process Improvements

The washability analysis data of the middlings stream revealed the importance of recycling the material to the feed especially if the unit is being used to produce a clean coal concentrate as opposed to being a deshaler. As shown in Table 15, about 35% of the middling material was high quality 1.40 float coal. Combining the 1.4 float with the coal in the 1.40 x 1.60 density fraction would yield a product containing about 10% ash and representing nearly 46% of the feed mass. Thus, including the middling stream with the tailings material in an effort to produce a low ash product would not be an optimum economical option.

Table 15. Particle density-by-density weight and ash distribution in the middling material collected during a typical FGX test.

Relative Density Fraction	Weight (%)	Ash (%)
1.40 Float	35.33	6.40
1.40 x 1.60	10.52	23.66
1.60 x 1.80	7.98	37.54
1.80 x 2.00	7.06	53.45
2.00 x 2.20	9.4	72.20
2.20 Sink	29.8	88.87
Total	100.00	44.70

To estimate the effect of recycling the middlings stream to the feed stream, a linear analysis was performed based on the flow diagram in Figure 10. If *F*, *P*, *M*, *L* and *T* are the mass flow rates of their respective streams, the overall recovery R_o can be determined according to the following expression:

$$\begin{aligned} P &= L R_1 \\ T &= L(1-R_1)(1-R_2) \\ R_o &= \frac{P}{F} = \frac{P}{P+T} = \frac{L R_1}{L R_1 + L(1-R_1)(1-R_2)} = \frac{R_1}{R_1 + (1-R_1)(1-R_2)} \end{aligned} \qquad [2]$$

where R_1 and R_2 are the partition numbers associated with the probability of a particle in a density fraction to report to the product and middlings stream, respectively.

Using data from washability analyses of each process stream and the resulting partition numbers, the overall circuit recovery values for particles in each density fraction were determined using Eq. [2]. As shown in Figure 11, recycling the middlings stream is predicted to provide a significant improvement in separation efficiency as indicated by a decrease in the Ep value from 0.24 without recycle to 0.17, which equates to a 40% efficiency improvement. Middlings recycle also allows the rejection of about 95% of the high density rock while recovering nearly 100% of the 1.6 float material. As a result, middlings recycle will be incorporated into a future test program.

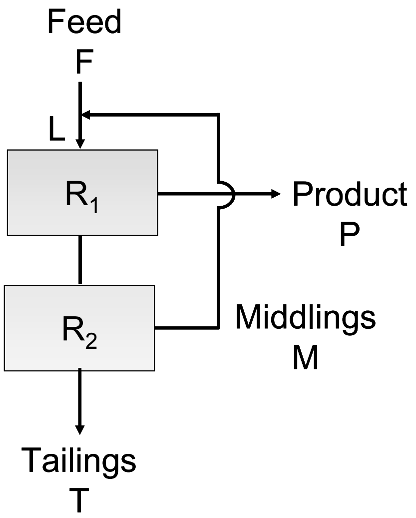


Figure 10. Flow diagram representing the recycle of the middlings stream to the feed stream of the FGX unit.

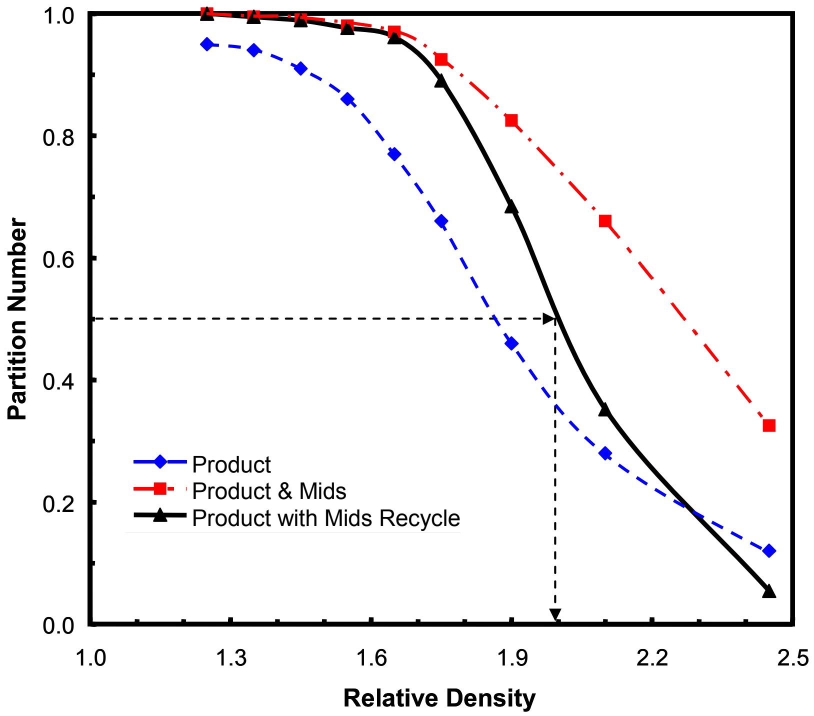


Figure 11. Predicted separation performance improvement provided by middlings recycle.

4.1.2 Powder River Basin (Wyoming) 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 feed coal was screened to achieve a nominal 50 x 6.3mm particle size fraction to feed the dry separator. During the PRB parametric studies, the table products were sampled in 5 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 16 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%.

Table 16. FGX Separator Performances from the Treatment of PRB Sub-Bituminous coal.

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

4.1.3 Gulf Coast Lignite Coal (Texas)

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

i. Reduce the total sulfur content of coal that is not marketable as a direct ship product;
ii. Decrease the mercury content;
iii. 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 Table 17 and Figure 12. 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 in the product of less than 10 lbs/T-Btu was generally achieved.

Table 17. Optimum separation performance summary from the treatment of the PRB coal.

Test	Product Ash %	Product Yield %	Ash Reduction %	Sulfur Reduction %	Mercury Reduction %
1	5.03	85.81	33.15	28.42	65.24
2	4.90	83.16	34.27	56.76	56.13
3	4.84	83.13	32.84	47.68	67.12
4	4.23	80.66	43.13	41.51	67.66

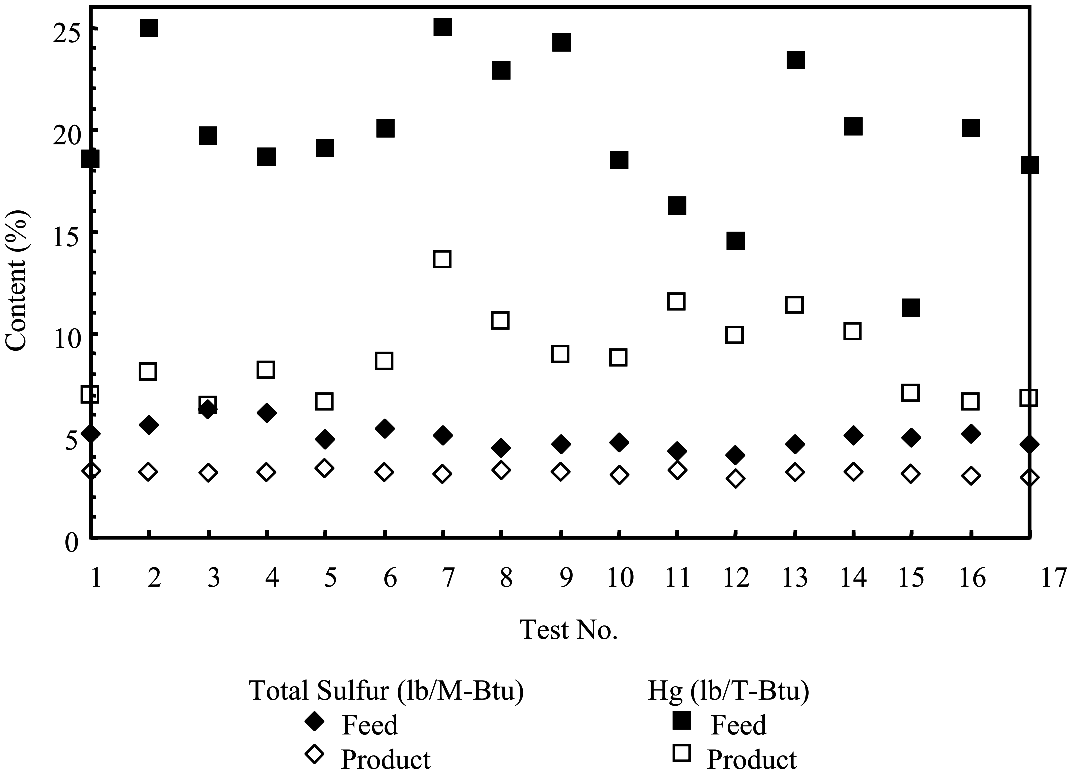


Figure 12. FGX separator sulfur and mercury reduction performances for Gulf Coast Lignite coal.

4.2 Eastern U.S. Coal Test Program

4.2.1 Central Appalachia Coal (Virginia)

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. 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 18, 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.

Table 18. Separation performance achieved on a run-of-mine Virginia bituminous coal.

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

4.2.2 Central Appalachia Coal (West Virginia)

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 19). 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.

Table 19. FGX Reject Analysis from the Treatment of a West Virginia Bituminous Coal.

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

4.2.3 Central Appalachia Coal (Kentucky)

A major coal producer in eastern Kentucky has large haul distances from their mine sites to the wet coal cleaning facilities. The use of a dry cleaning system at the mine site was evaluated to evaluate the feasibility of rejecting the high density rock at the mine site and avoid the transportation, processing and storage costs at the wet cleaning facility. The tests involved raw coal from 3 separate deep mine sources and seams. The Falcon raw coal from the Hagy seam is delivered by truck with a haul distance of 19 miles (one way). The Snapco raw coal from the Splashdam seam is delivered by truck with a haul distance of 18 miles. The Elkhorn No. 2 raw coal from the Alma seam is delivered by truck with a haul distance of 23 miles.

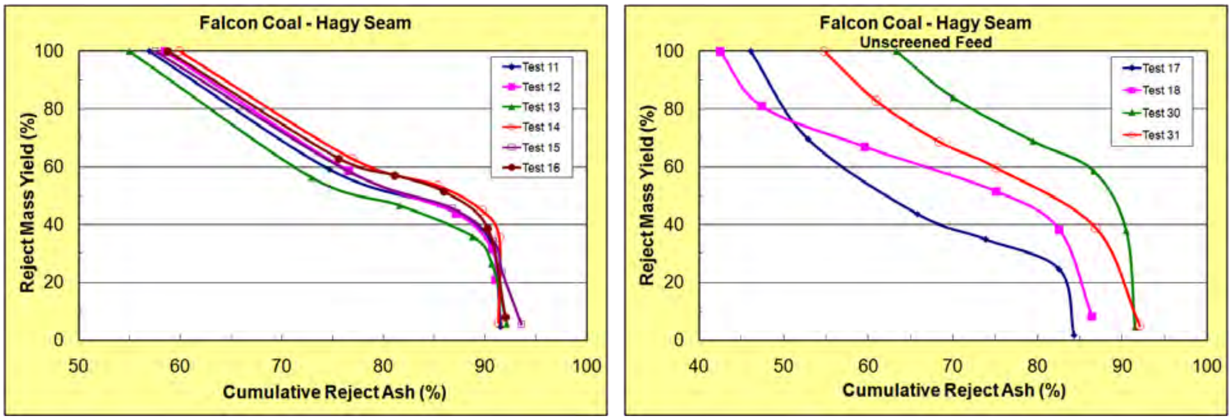
The separation performance results discussed in the sections to follow are based on cumulative yield and ash content reporting to the reject stream. The results for the tests with prescreened feed include a representative portion of the screen underflow (-6mm material) and baghouse dust combined with the first product sample split from the deck.

Falcon Coal – Hagy Seam

1. A total of 12 tests were performed on the Falcon raw coal under varying operating conditions including experiments with screened and unscreened feed. A vibrating screen with 6mm (¼ inch) aperture was used for prescreening purposes.

2. The separation performance results achieved on the prescreened coal over a range of operating parameter values were relatively consistent.

3. Based on the performance results, the optimal conditions appear to be represented by Test 14 where approximately 45% of the material can be rejected by applying the FGX technology and the rejected material will have an ash content of near 90%. The results are showed in Figure 13-a. The results also indicated that as much as 57.5% of the total 6mm (+¼ inch) Falcon raw coal can be rejected with an ash content of 89%.



a b

Figure 13. Separation performance for the Falcon Coal with the feed screened at 6mm (¼ inch) (a) and with unscreened feed (b).

4. The performance results achieved on the unscreened ROM raw coal was similar to those achieved on the prescreened material. As shown in Figure 13-b, a relatively sharp separation was obtained during Test 30 which indicates that 37.9% of the total feed can be rejected with the reject material having an ash content of 90.5%. Test 30 also represented the feed with the highest feed ash content (63.3%). Tests 17 and 18 were also tests with unscreened feed and had a larger portion of -¼ inch material, 56% and 52%, respectively. The higher fraction of fine material appears to degrade the separation performance.

5. Two tests were conducted with screened feed to evaluate the effect of increasing the mass feed flow rate for the unit with the Falcon raw coal. The performance results for Tests 40 and 41, shown in Figure 14, indicate that under the operating conditions for Test 40 approximately 20% of the total feed can be rejected with an ash content of 91% in the rejected material.

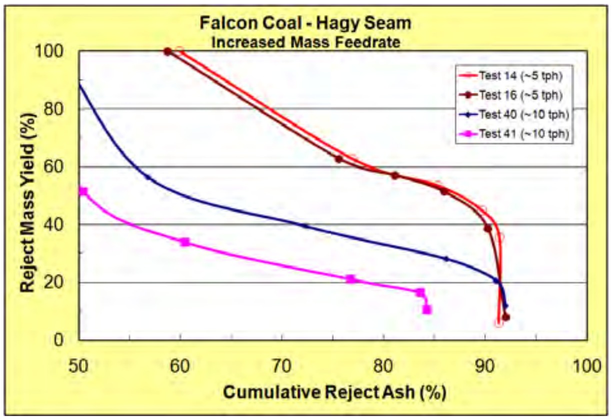


Figure 14. Separation performance for the Falcon Coal with increased mass feedrate screened at 6mm (¼ inch) compared with standard feedrate.

Snapco Coal – Splashdam Seam

1. A total of 5 tests were performed on the Snapco raw coal representing coal from the Splashdam seam, a high ash feed (>60%), under varying operating conditions including experiments with screened and unscreened feed. A vibrating screen with 6mm (¼ inch) aperture was used for prescreening purposes.

2. The separation performance results on the high ash feed indicated that the FGX technology can be used to reject about 25% of the total raw feed while producing a reject containing near 87% ash. All the tests for the screened feed produced similar results as shown in Figure 15.

3. Similar results, also shown in Figure 15, were achieved on the unscreened raw feed. The findings indicate that about 27% of the total Snapco ROM coal can be rejected with an ash content of about 87%.

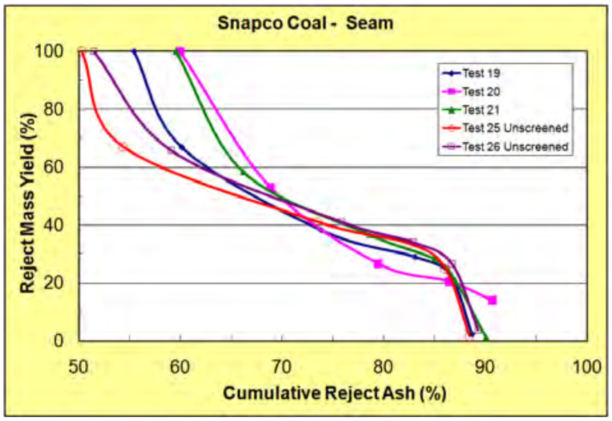
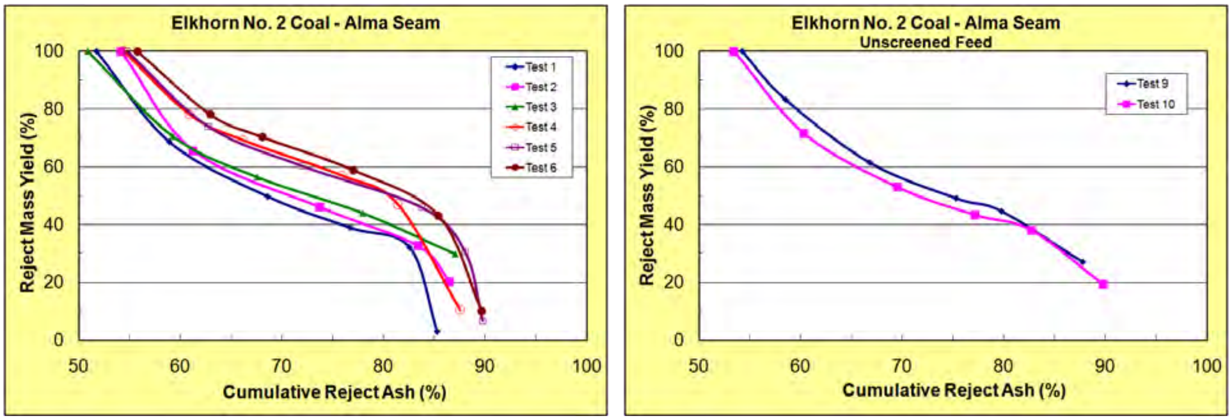


Figure 15. Separation performance for the Snapco Coal with the feed screened at 6mm (¼ inch) and with unscreened feed.

Elkhorn No. 2 Coal – Alma Seam

1. A total of 11 tests were performed on the Elkhorn No. 2 raw coal under varying operating conditions with prescreened and unscreened feeds. A vibrating screen with 6mm (¼ inch) aperture was used for prescreening the feed for the first 9 tests.

2. The results for Tests 1 – 6 are shown in Figure 16-a. The best ash rejection performance for the Elkhorn No. 2 coal was produced under slightly different operating conditions than for other coals tested. For Tests 5 and 6, the deck length-wise slope was set at 0.5 degrees less than that which has been found to be optimal for other coals. These tests indicate that approximately 36% of the nominal +6mm (+¼ inch) Elkhorn No. 2 feed can be rejected with an ash content of 88% for the rejected material.



a b

Figure 16. Separation performance for the Elkhorn No. 2 Coal with the feed screened at 6mm (¼ inch) (a) and with unscreened feed (b).

3. The results for the unscreened feed, shown in Figure 16-b, indicate a marginal potential for good separation. Although the results indicate that the high density material can be separated from the feed, the loss of coal to the reject increases significantly as the amount of reject increases.

4. Three additional tests were conducted using the Elkhorn No. 2 raw coal to determine the effect of feed mass flow rate on the separation performance. As shown in Figure 17, at a feed rate of approximately 50% more than the standard test conditions (Test 7), the separation performance appears to be similar to the best performance for the 6mm (+¼ inch) screened feed (Tests 5 and 6).

The results presented for the three coals are conservative in that the amount of coal loss is minimal given the relatively high reject ash contents. An additional amount of material could be rejected economically if the loss of a small amount of coal is balanced with the cost of transportation.

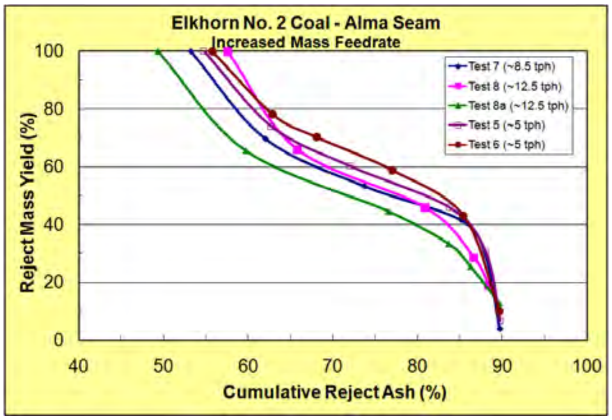


Figure 17. Separation performance for the Elkhorn No. 2 Coal with elevated feed mass flow rates.

4.3 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 +6mm (+1/4-in) 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 20 details the separation performance achieved along the length of the table under the optimum operating conditions. A separation between the 4th and 5th 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 20. FGX Separation Performance on Kentucky coarse gob.

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			

A second coarse reject material was evaluated at a site in Virginia. The feed contained 77.6% plus 6.3mm (1/4-in) material and 55.54% ash. The amount of 1.8 RD float material in the plus 6.3mm (¼-in) 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 21). 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 21. FGX separation performance on Virginia coarse gob.

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		

Based on washability data and the results presented in Table 20, 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.

5.0 TECHNICAL 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. The dry cleaning process 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 10000 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.

The results from the Gulf Coast lignite tests resulted in the installation of the first FGX coal cleaning facility in the U.S.. The full-scale facility processes the +6mm (+1/4-inch) particle size fraction. Approximately 250 tph of material are processed across two table decks with the primary objectives of maximizing total sulfur and mercury rejections while recovering greater than 92% of the energy value in the feed coal.

Specific conclusions generated from the project include:

1. The FGX dry density-based separator is ideal for achieving high density separations in situations where the objective is to maximize rock rejection while avoiding the loss of coal. The density cut point achievable is 1.8 RD or greater.

2. The separation yields a middlings stream that is comprised of a mixture of low-density coal and high-density rock. The amount of material in the middlings stream is dependent

on the operating parameter values and feed coal characteristics (particle size and density distributions as well as particle shape.

3. Visual observations revealed that particle shape has an impact on the separation performance. Reject particles that are flat or saucer shaped tended to report to the clean coal stream.

4. If little or no material exists in the 1.6 x 2.0 specific gravity fractions in the feed, the FGX separator can provide a high quality product that may meet contractual end-user requirements.

5. A percentage of fine, high-density particle by-pass to the product stream occurred and is expected since the fluidized particle bed is comprised of the high ash material and there is no method of preventing the material from overflowing. The amount of fine, high density by-pass was measured to be around 20% in a process efficiency evaluation conducted in this study.

6. The throughput capacity appears to be relatively high at around 5 – 10 tph/m^2.

7. Longitudinal slope and table frequency appear to be the critical operating parameters that control both coal recovery and product grade. Longitudinal slope was manipulated with respect to the amount of high-density reject in the feed. When the feed contained a large amount of high-density material (i.e., greater than 50% ash-bearing material), a low slope of 0.5^O was used which provided less resistance for the reject when moving toward the reject discharge end of the table. A slope of 1.5^O provides greater resistance to movement which holds back the reject discharge rate and allows a fluidized bed of sufficient depth to provide optimum coal recovery. Adjusting table frequency has similar effects on performance.

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7.0 PRODUCTS PRODUCED OR TECHNOLOGY TRANSFER ACTIVITIES

7.1 Publications

i. Honaker, R. Q., Luttrell, G. H., Bratton, R and. Patil, D., “Improving Mine Profitability Using Dry Deshaling Technologies,” *Proceedings*, 31st International Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, Paper No. 49, May 21-25, 2006.
ii. Honaker, R. Q., Luttrell, G. H. and Lineberry, G. T., “Improved Coal Mining Economics Using Near-Face Deshaling, *Minerals and Metallurgical Processing Journal*, Vol. 23. No. 2, pp. 73 – 79, 2006.
iii. Honaker, R. Q., Luttrell, G. H., Bratton, R., Saracoglu, M, Thompson E., and Richardson V., “Dry Coal Cleaning Using The FGX Separator,” *Proceedings*, 24th International Coal Preparation Conference, Lexington, Kentucky, pp. 19 – 36, April 30 – May 3, 2007, pp. 61 - 76.
iv. Honaker, R. Q., “Dry Coal Cleaning Technologies for India Coal,” Workshop on Coal Beneficiation and Utilization of Rejects: Initiatives, Policies & Best Practices, Ranchi, India, August 22 – 24, 2007.
v. Honaker. R. Q.., Saracoglu, M., Luttrell, G. H., Bratton, R. and Richardson, V., “Dry Coal Cleaning using the FGX Separator,” *Proceedings*, South African Coal Preparation Conference, Johannesburg, South Africa, September 11 – 13, 2007.
vi. Honaker, R. Q.,. Saracoglu, M. Thompson, E. Bratton, R Luttrell G. H. and Richardson, V., “Upgrading Coal Using A Pneumatic Density-Based Separator,” *International Journal of Coal Preparation and Utilization*, Vol. 28, No. 1, pp. 51 – 67, 2008.

7.2 Networks or Collaborations Fostered

During the project, several companies have expressed interest in evaluating the technology and concept through in-field tests or process performance projections. The companies outside the project team include:

1. Consol Energy;
2. National Coal;
3. Andalex;
4. American Electric Power;
5. Arch Coal;
6. Coaltech;
7. Tampa Electric Coal (TECO);
8. Alpha Natural Resources;
9. Luminant Mining.

The collaboration with Luminant Mining led to a commercial installation of a 600 tph dry coal cleaning facility near Oak Hill, Texas. The FGX tables treat the +6mm particle size fraction at a throughput capacity of 250 tph. The main objective of the facility is to reduce the total sulfur and mercury contents. The operation was brought on-line around June 2008.

Presentations have been provided to several companies and organizations including the East Kentucky Coal Preparation Society (February 2006) and the Annual Society for Mining, Metallurgy and Exploration meeting in St. Louis (March 2006).

The research findings have also been presented to coal operators and plant designers in the countries of Brazil (September 2007), South Africa (September 2007) and India (August 2007). The conversations and subsequent testing on Brazilian coals resulted in a commercial installation of the FGX separator by a U.S. manufacturer. The promising results for the project also resulted in a funded project to investigate the potential for cleaning India coals. The project is being sponsored by the U.S. Department of State.

7.3 Inventions/Patent Applications

There were no invention/patent applications filed as a result of work performed in this project.