FINAL TECHNICAL REPORT
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Project Title: **DEVELOPMENT OF A DRY PREPARATION PLANT FLOWSHEET FOR CLEANING ILLINOIS COAL**

ICCI Project Number: 11/4A-1
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ABSTRACT

Dry cleaning has received renewed interest in the coal industry due to relatively higher costs and more difficult environmental issues associated with traditional wet coal preparation methods. After an earlier evaluation of the FGX Dry Separator funded by the ICCI, the main objective of this study was to develop a complete dry preparation plant flowsheet for cleaning the entire run-of-mine coal stream produced by an Illinois coal mine. The proposed flowsheet consists of a rotary breaker to lower the top-size of run-of-mine coal and achieve preliminary de-shaling, the FGX Dry Separator for cleaning coarse (i.e. +5-mm) coal, and a new air table for fine coal cleaning.

Samples were collected from the rotary breaker at a nearby coal preparation plant and evaluated to determine the unit's efficiency at removing rock and breaking run-of-mine coal to 3-inch top size. Then, a 5-ton sample of rotary breaker product was cleaned using a 10-tph FGX Dry Separator at the Illinois Coal Development Park. A statistically designed experimental program verified the significant role played by -5-mm fine coal during FGX coarse coal cleaning. When FGX middlings product is crushed from 3-inch to 1-inch top size and re-cleaned, total ash rejection in the clean product is improved from 20% to 37% while maintaining combustible recovery at 90%.

The FGX Dry Separator was found to be unsuitable for effective fine coal cleaning; however, extensive testing provided insight into the development of a new air table designed specifically for dry cleaning of fine coal. Testing conducted with an experimental separating deck and fluidization air system indicate that its fine coal cleaning performance is the same or better than the coarse coal cleaning performance achieved by the FGX system.

Testing the complete dry separation plant (consisting of a rotary breaker, the FGX Dry Separator, and a fine coal air table) on an Illinois No. 6 coal having 33.4% ash and 3.73% sulfur in the feed produced a clean coal yield of 68.8% at 16.0% ash and 3.12% sulfur with a resulting tailings ash and sulfur of 71.6% and 5.06%, respectively. An economic analysis of this flowsheet estimated that total capital and operating costs per raw and clean ton are $1.94 and $2.81, respectively. Operating costs alone would be $1.18 and $1.71 per ton of raw coal and clean coal, respectively. These cost figures are significantly better than the cost of coal cleaning realized using wet preparation plants.

EXECUTIVE SUMMARY

The current practice of wet coal cleaning has created numerous tailings ponds, not only in Illinois, but all over the country. Although dense medium wet cleaning of coarse coal is highly efficient, wet cleaning and dewatering of fine coal continues to pose challenges to coal operators. Due to relatively higher costs of fine coal cleaning and dewatering, many plant operators discard the fine (-150-micron) coal fraction of run-of-mine coal to coal slurry ponds, which creates environmental problems and negative public perception. In addition, direct rejection of fine coal results in loss of recoverable clean coal and the revenue it could generate.

In a previous ICCI-funded study by Mohanty (2010), the FGX Dry Separator was shown to successfully clean coarse coal at much lower cost in comparison to commonly used wet coal cleaning methods. The best density-based cleaning performance obtained from the FGX Dry Separator was described by an effective separation density (SG_{50}) of 1.98 and probable error (E_p) of 0.17 for 2.5-inch x 4-mesh (~5-mm) coal. The cost of coarse coal cleaning with the FGX Dry Separator was estimated to be only $0.91/ton of raw coal (and $1.56/clean ton) based on cost information obtained from the first full-scale FGX installation in the US (Ohio) and technical data generated in the project from FGX cleaning of Illinois coal. Although using a dense medium wet coal cleaning system results in much better cleaning performance in terms of SG_{50} and E_p (1.6 and 0.03, respectively), the operating cost of such a system is reportedly much higher at $2.52/clean ton (Laurila, 1998).

Building on these findings and addressing some of the recommendations of the previous study on the FGX Dry Separator, the present study aimed at developing a complete dry separation plant flowsheet to clean the entire (both coarse and fine) run-of-mine coal. The proposed flowsheet consists of a rotary breaker (with 3-inch apertures) to achieve raw coal sizing and preliminary separation of large rock from run-of-mine coal; a FGX Dry Separator to clean 3-inch x 4-mesh coal; and a new air table for cleaning fine (-5-mm) coal. Bulk run-of-mine coal was processed in a rotary breaker operating at Knight Hawk Coal Company's Prairie Eagle Mine and samples of feed, product, and reject streams were collected and analyzed to characterize the performance of the rotary breaker. Next, five tons of rotary breaker product were processed in the 10-tph FGX test unit located at the Illinois Coal Development Park to determine: 1) the optimum proportion of fine coal in the feed stream for obtaining the best separation performance for coarse coal cleaning, 2) the separation performance of the FGX Dry Separator for fine (-5-mm) coal cleaning, and 3) the separation performance of a two-stage FGX system with crushing and re-cleaning of the first stage middlings stream.

Rotary breakers are widely known for minimal coal loss to the reject stream. This was verified again for the rotary breaker operating at the Prairie Eagle plant. Reject was only 0.15% of the feed and consisted of about 7.94% low ash (11.20%) coal. The FGX Dry Separator was then used to clean the 75-mm x 5-mm size fraction of the rotary breaker product. Empirical models developed using a Central Composite Design and response surface methodology showed that the percentage of fine coal in the feed had a significant

effect on tailings ash, product ash, and separation efficiency achieved for coarse coal cleaning. Ash cleaning results after second stage FGX cleaning indicated that significant improvement in overall cleaning performance was achieved when first stage middlings were crushed to 1-inch top-size prior to going through second stage cleaning. Ash rejection improved from 20% to 37% while maintaining 90% combustible recovery when two-stage cleaning with intermediate crushing was used.

The FGX Dry Separator was found to be ineffective for fine coal cleaning; however, extensive testing conducted with the FGX Dry Separator provided insight into developing a new air table suitable for dry cleaning of fine coal. Findings from this study suggest that the new air table must have a much better fluidization air distribution throughout the deck, which will require a completely different deck and possibly a much different vibration frequency and angle of vibration. All of these parameters require further evaluation; however, preliminary tests conducted with a new air table deck showed that very good separation with high combustible recovery of more than 90% could be achieved while rejecting more than 40% of ash forming materials. Additional fine coal cleaning tests conducted on a second coal sample collected from Prairie State Generating Company's Lively Grove Mine achieved even better ash rejection (>50%) at greater than 90% combustible recovery.

The dry separation plant flowsheet developed in this study could provide a clean coal yield of 68.8% at 16.0% product ash and 3.12% sulfur from Prairie Eagle coal having 33.4% feed ash and 3.73% sulfur. Tailings ash and sulfur were 71.6% and 5.06%, respectively. In comparison, the current wet coal preparation plant serving the Prairie Eagle Mine provides a clean coal yield in the range of 60 to 67% at a product ash of ~9.5% (on a dry basis) and a product sulfur content of ~3.25% (Stanley, 2012). The moisture content of the current plant product is ~13.5%, whereas the moisture content of the dry separation plant product would be very close to the inherent moisture in Prairie Eagle's coal, which is about 8%. In reporting these results, it should be noted that although the dry separation plant product ash of 16.0% may appear high in comparison to that of the clean coal produced by a conventional wet plant, the heating value, which is directly related to the arithmetic sum of ash and moisture content, would be nearly equal for both clean coal products.

Based on a preliminary economic analysis of the entire dry separation plant flowsheet, it is estimated that total capital and operating costs per ton of raw coal feed and clean coal product are $1.94 and $2.81, respectively. The operating cost alone would be $1.18 and $1.71 per ton of raw coal and clean coal, respectively. It is recommended that a follow-on study be pursued to further develop the new air table for improving the effectiveness of fine dry coal cleaning and establishing a complete dry separation plant flowsheet for cleaning the entire run-of-mine coal in Illinois and elsewhere.

OBJECTIVES

The main goal of this study was to evaluate a complete dry preparation plant flowsheet for cleaning run-of-mine (ROM) Illinois Basin coal. Specific project objectives were:

- To evaluate a rotary breaker for its preliminary de-shaling efficiency.
- To further optimize FGX Dry Separator performance for coarse coal cleaning, with respect to the optimal content of fines in feed coal and two stage cleaning with a middlings recycle circuit that includes intermediate crushing.
- To evaluate FGX Dry Separator performance for cleaning fine coal in the size range of -4-mesh (~ 5-mm).
- To conduct an economic analysis to estimate dry coal cleaning costs: capital ($/ton-per-hour of installed capacity) and operating ($/ton of raw coal processed and clean coal produced) based on the proposed dry separation plant flowsheet.

INTRODUCTION AND BACKGROUND

Most of the coal in Illinois is cleaned using a variety of wet processes including heavy medium cyclones, jigs, spirals, and froth flotation. The use of water as medium increases the separation efficiency of these processes; however with a concomitant generation of large volumes of fine coal slurry. Nearly half of the coal preparation plants in the US dispose of these fine coal slurries to impoundments or ponds to avoid the relatively high cleaning and dewatering cost associated with fine coal. This causes environmental problems as well as a huge loss of recoverable clean coal. These phenomena have created a renewed interest in dry separation processes and a few century-old dry separation techniques, like air tables and air jigs, have been updated with the best available modern technologies. Dry coal beneficiation is typically less restrictive, simpler in process, and easier to operate, and therefore could be suitably utilized to produce a final clean coal product or to produce an intermediate product that can be further cleaned using a wet preparation plant if required.

Based on the dry coal cleaning test experience with the FGX Dry Separator, the principal investigator originally believed that with certain modifications to operating process variables, the FGX Dry Separator may also be able to effectively clean the fine coal fraction and a plant flowsheet like the one shown in Figure 1 was proposed. The flowsheet includes a rotary breaker with 3-inch apertures to achieve preliminary separation of large rocks from ROM coal, followed by two FGX Dry Separators operating at distinctly different operating conditions to achieve the best possible cleaning performance for coarse (3-inch x 4-mesh) and fine (-4-mesh) coal. Both pieces of equipment are described below. The flowsheet also includes two stages of FGX cleaning with intermediate crushing of combined middlings and tailings from the first stage to minimize clean coal loss to the reject stream thereby enhancing clean coal recovery. However, the modified FGX Dry Separator was found to be unsuitable for fine coal cleaning. Consequently, a new air table was envisioned for cleaning fine coal and the proposed dry cleaning flowsheet was adjusted accordingly.

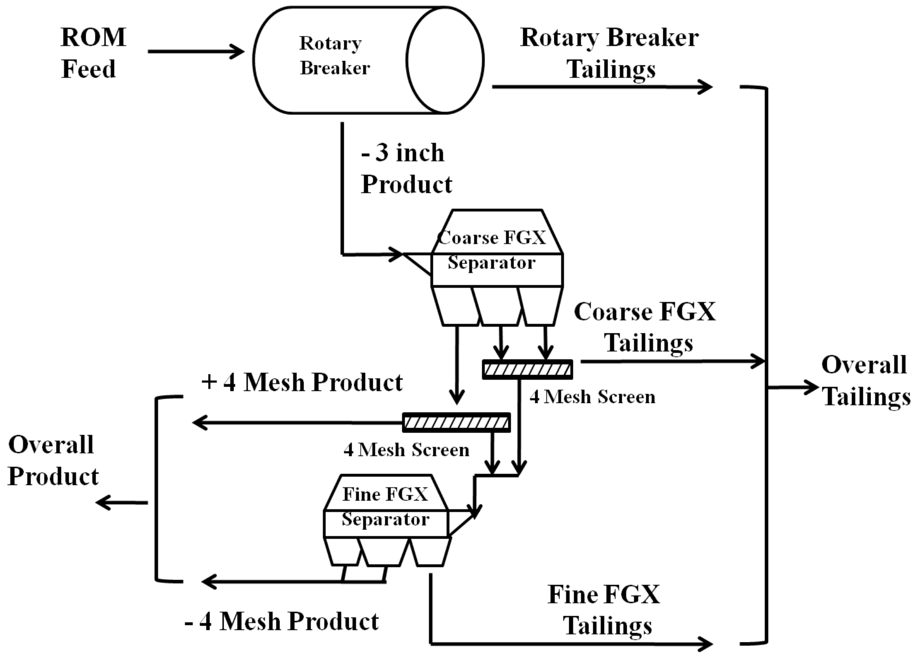

Figure 1: Originally proposed flowsheet for dry cleaning of ROM coal.

The rotary breaker is known to be highly effective at de-shaling or removing large rocks from ROM coal. It utilizes the principle of selective breakage for coal, which is generally softer and easier to break than rock. As shown in Figure 2, a rotary breaker consists of a large diameter cylinder with perforated screen plates forming the cylindrical surface. The aperture size of these screen plates is the top size to which ROM coal is reduced. The efficiency of the rotary breaker depends on the cylinder diameter-to-length ratio and rotation speed, which control the number of drops as well as the height of drops to break ROM coal to the required size. Coal is continuously fed into the breaker cylinder where screening of smaller material occurs quickly followed by selective breakage of large lumps through the process of repeated lifting and dropping against the strong, perforated screen surface resulting in the desired size reduction and further screening. Material passing through screen openings is sent to the preparation plant for further cleaning, while screen overflow material consisting mostly of unbroken hard rock is discharged as tailings and discarded.

The rotary breaker can effectively treat run of mine coal up to 6-inch in size and provide a relatively uniform -3-inch product (Bhattacharya, 2006). The product is easier to clean by the subsequent cleaning processes than ROM coal due to better coal liberation and lower impurity content. The rotary breaker has the advantage of being robust with low operating costs typically ranging from $0.01 to $0.04 per ROM ton. It has high capacity reaching as much as 2000 tons per hour (tph). It is also considered environmentally friendly (Bhattacharya, 2006). Operating noise and dust issues are usually overcome by locating the rotary breaker some distance away from the coal preparation plant and/or having proper sound- and dust-proof enclosures.

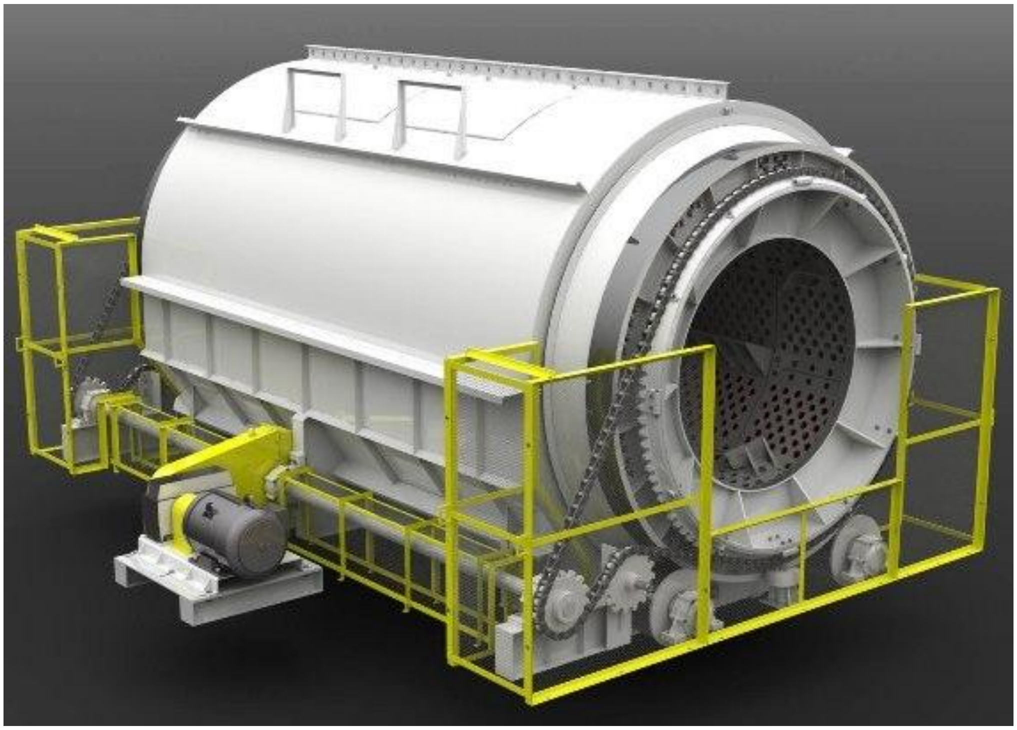

Figure 2: Rotary breaker (Elgin National Industries, Inc., 2010).

The FGX Dry Separator was shown to be an effective dry coal cleaning system for coarse coal in a previous ICCI-funded project (Mohanty, 2010). It consists of a perforated separating deck supported by a suspension system and actuated by a vibrator mechanism with air chambers below the deck through which air flow is supplied by a blower, as shown in Figure 3. The separating deck has riffles on its surface to guide material flow. It is suspended in an inclined position both in the longitudinal and transverse direction as shown with angles of inclination being a process parameter that can be adjusted as desired. Air flow fluidizes feed material on the deck and the vibratory mechanism imparts a helical turning motion to particles moving across the deck causing particle stratification to occur on the separating deck. Coal particles being less dense are thrown up higher in comparison to heavy middlings and pure rock particles, which stay in contact with the deck surface and get pushed to the tailings (far) end of the deck by the continuous flow of feed material. As coal particles rise to the top of the stratified layers on the deck, they are discharged over the baffle plate into the clean coal port at the feed (near) end of the deck.

The earlier study found that the presence of fines (-5-mm size coal) in the feed improved coarse coal cleaning performance significantly. The best ash separation efficiency was achieved at 29% fines, whereas the best sulfur rejection was achieved at 18% fines. A limited number of tests conducted with 93% -5-mm feed indicated that reasonably good levels of ash and sulfur cleaning could be achieved by the FGX Dry Separator processing fine coal. For an easy to clean ROM coal, only 0.42% of clean coal in the feed was lost to the tailings stream, whereas 95.5% was recovered to the product. For a difficult to clean ROM coal, 1.0% of clean coal in the feed was lost to the tailings stream, whereas

93.1% was recovered to the product. Economically, total (capital, installation, and operating) costs for cleaning Illinois coal using the FGX Dry Separator were estimated to be $0.91/ton of raw coal and $1.56/ton of clean coal. Operating costs alone were estimated to be $0.69/ton of raw coal and $1.19/ton of clean coal. The payback period for a full-scale FGX Dry Separator having a feed handling capacity of 120 tph was estimated to be approximately one month.

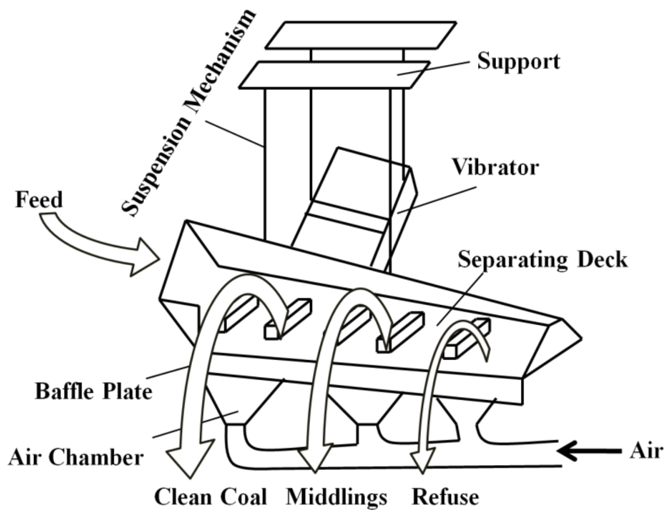

Figure 3: Schematic of FGX Dry Separator (Lu *et al*., 2003).

Based on recommendations of the previous ICCI-funded study, the main goal of this study was to develop a dry preparation plant flowsheet for cleaning Illinois Basin coal having a rotary breaker for de-shaling ROM coal and an optimized FGX system for cleaning both coarse and fine fractions of the rotary breaker product. When the FGX Dry Separator failed to provide effective cleaning for the fine fraction, development of a new air table was initiated for cleaning coal finer than ~5-mm in size.

EXPERIMENTAL PROCEDURES

Bulk run-of-mine (ROM) coal was processed by the rotary breaker at Knight Hawk Coal Company's Prairie Eagle Mine with representative samples collected from feed, product, and tailings streams. These samples were analyzed for size-by-size characterization to determine the ROM coal cleaning performance of the rotary breaker. Then five tons of the rotary breaker product were transported to the Illinois Coal Development Park (ICDP) for further cleaning by the FGX Dry Separator.

FGX SepTech, LLC provided the 10-tph FGX Dry Separator prototype unit shown in Figure 4, which was set up at the ICDP along with a small conveyor for feeding the unit. FGX testing included coarse and fine coal cleaning, two stage cleaning with intermediate crushing, and deck modifications for improved fine coal cleaning.

Figure 4: FGX SepTech LLC's 10-tph FGX Dry Separator test unit.

RESULTS AND DISCUSSIONS

Task 1: ROM Coal Cleaning by Rotary Breaker

Rotary breakers are known to lose very little coal, but also not reject but only the largest pure rock type materials. This was confirmed by the float/sink analysis conducted on Prairie Eagle rotary breaker product and reject samples. As shown in Table 1, there was not much difference between the quality of rotary breaker product and feed even if it was able to reject some rock type materials having ash content greater than 76%. This was caused due to the rejection of only a limited proportion of rocks present in the feed indicated by rejection of only 1.9% of the feed to the tailings stream. It can be seen in the float/sink analysis on the rotary breaker reject that about 7.94% consisted of low (11.20%) ash coal; however, overall it was a very small percentage (0.15%) of the ROM feed.

Rotary breaker product used as feed for the FGX Dry Separator went through a size-by-size analysis. Weight, moisture, and ash for each size fraction are listed in Table 2. Approximately 37% of the rotary breaker product is -4-mesh. The +4-mesh material (sum of +2-in, 2-in×1-in, 1-in×1/2-in, and 1/2-in×4-mesh) which could be effectively cleaned by the FGX Dry Separator had approximately 33% ash and 3.95% of total sulfur.

Table 1: Float/sink analysis of rotary breaker product and reject samples.

Mean SG	Product Yield% = 98.10		Reject Yield% = 1.90		Reconstituted Feed	
	Wt%	Ash%	Wt%	Ash%	Wt%	Ash%
1.25	47.53	8.28	2.26	6.00	46.67	8.28
1.45	10.31	15.87	5.68	13.27	10.22	15.84
1.80	15.79	42.00	8.01	52.28	15.64	42.10
2.40	26.37	77.08	84.05	84.97	27.47	77.54
Total	100.00	32.53	100.00	76.49	100.00	33.37

Table 2: Characteristics of rotary breaker product for FGX testing.

Size Fraction	Weight, as received (%)	Moisture (%)	Ash, dry basis (%)	Total Sulfur, dry basis (%)
3 in × 2 in	5.11	4.88	51.81	3.96
2 in × 1 in	21.03	6.62	34.55	4.06
1 in × 1/2 in	16.26	6.73	30.32	4.11
1/2 in × 4 mesh	20.57	6.58	28.40	3.72
- 4 mesh	37.04	7.82	32.15	3.29
Total	100.00	6.98	32.61	3.71
+ 4 mesh	62.96	6.49	32.88	3.95

Task 2: FGX Dry Separator Testing

Task 2.1: Effect of Fine Coal in Feed on Coarse Coal Cleaning Performance: One of the primary objectives of this study was to investigate the effect of fine (-5-mm) coal in the feed to the FGX Dry Separator on the separation efficiency it achieves for coarse (+5-mm) coal cleaning. Conventional wisdom suggests that higher percentages of fine coal help form a better fluidized bed of coal on the separating deck. The absence of fine coal in the feed creates bubbly zones from the upward air flow through the coal bed on the FGX deck, which is detrimental to cleaning efficiency. To test this phenomena, roughly two tons of rotary breaker product were screened at 4-mesh to control the amount of fine coal added to +4-mesh feed as required by each experimental design.

A Central Composite Design (CCD) experimental program was conducted for this task. Three factors selected for this investigation based on prior experience with the FGX Dry Separator were feeder frequency (in the range of 25 to 35 Hz), deck vibration frequency (in the range of 25 to 55 Hz), and the percentage of fines (in the range of 10 to 40%). A total of 18 experiments were conducted. Operating conditions and resulting coal cleaning performance obtained for each experiment are listed in Table 3.

Empirical models were developed for tailings ash, product ash, ash separation efficiency, and sulfur rejection using the stepwise regression technique. These models are described as follows:

$$\text{Tailings Ash (TA) \%} = 76.81 + 4.81 * A - 11.13 * A^2 \quad [1]$$

$$\text{Product Ash \%} = 20.96 - 3.01 * A - 0.090 * B - 4.91 * C + 2.99 * A * C + 2.27 * B * C \quad [2]$$

$$\text{Separation Efficiency (Product+Middlings) \%} = 26.36 + 4.83 * A - 3.48 * B + 17.27 * C \quad [3]$$

$$\text{Sulfur Rejection \%} = 19.9 + 2.1 * A - 6.0 * B + 18.64 * C + 5.98 * A^2 \quad [4]$$

where A, B, and C are coded representations for fine particle percentage, feeder frequency, and bed frequency, respectively.

Table 3: CCD test conditions and results.

CCD Run ID	a*	b*	c*	Feed Ash (%)	P** Ash (%)	P** Sulfur (%)	M** Ash (%)	T** Ash (%)	CR*** (P+M) (%)	AR*** (T) (%)	SR*** (T) (%)
1	10	25	25	38.75	36.29	3.62	43.71	64.19	95.90	11.61	6.66
2	10	25	55	31.05	14.07	3.06	21.47	58.12	78.86	65.14	42.79
3	10	30	40	29.83	17.46	2.98	36.44	50.82	86.00	34.02	33.53
4	10	35	25	30.30	28.77	3.80	41.63	55.44	98.07	5.52	2.99
5	10	35	55	38.31	20.51	3.00	47.54	75.81	91.28	44.01	32.91
6	25	25	40	34.99	21.03	3.00	39.58	74.47	92.17	42.42	28.99
7	25	30	25	29.74	26.67	3.60	49.86	75.71	98.48	11.19	3.76
8	25	30	40	37.22	22.53	3.06	62.78	84.55	96.73	30.18	18.21
9	25	30	40	35.79	22.45	3.10	56.59	84.58	96.29	36.54	17.58
10	25	30	40	38.37	28.10	3.02	43.97	79.73	94.69	33.56	28.61
11	25	30	40	27.82	19.23	3.13	41.91	79.13	97.59	23.70	13.12
12	25	30	55	33.27	14.67	3.12	29.75	72.78	88.95	59.26	40.76
13	25	35	40	23.89	18.59	2.80	32.50	63.56	96.88	17.33	8.13
14	40	25	25	22.54	19.83	3.00	20.51	53.11	95.18	18.75	9.42
15	40	25	55	43.64	14.44	2.93	26.03	66.03	68.65	78.72	60.99
16	40	30	40	29.95	15.86	3.09	33.69	75.99	94.05	44.06	24.68
17	40	35	25	22.13	19.04	3.09	32.10	78.60	98.80	15.53	6.51
18	40	35	55	35.00	17.84	2.97	32.35	78.71	91.98	55.07	38.26

***: a=** -4-mesh (%); **b=**feeder frequency (Hz); **c=**deck vibration frequency (Hz)
: **P=product; **M**=middlings; **T**=tailings
***: **CR=**combustible recovery; **AR=**ash rejection; **SR=**sulfur rejection

Equation 1 indicates that tailings ash is primarily dependent on only one of the three factors varied during experiments: the percentage of fine particles in the feed. In addition, the second order relationship reveals that there is an optimum level of fines in the feed that produces the highest tailings ash. This optimum A can be found mathematically by differentiating Equation 1 with respect to A as follows:

$$\frac{dTA}{dA} = 4.81 - 22.26 * A \quad [4]$$

Then, for the optimum value of A, the right-hand side of Equation 4 has to be equal to zero implying that the optimum value of -4-mesh fines in the feed, in coded terms, is 0.216. The actual optimum value of A can be determined from the following expression:

$$A(coded) = \frac{\mathrm{A(actual)} - 25}{15}$$

$$\therefore \text{ A (actual)} = 28.24\%$$

In other words, the reject stream will have maximum ash content and minimal carbonaceous material when FGX feed has approximately 28% fine coal. It is believed that when the percentage of fine coal in the feed is below 28%, interstitial space (voids between coarse particles) is not suitably filled to form a properly fluidized bed, which is required for the proper stratification of high density rock and low density coal layers on the separation deck. On the other hand, when the percentage of fine coal in the feed is above 28%, the material bed on the separating deck may be too packed to be fluidized by the volumetric air flow rate, which was kept at a constant level during experiments.

Equation 2 indicates that the product ash response is affected by all three process parameters, i.e., fine particle percentage, feeder frequency, and deck vibration frequency. Interaction effects of feed fines percentage-deck vibration frequency and feeder frequency-deck frequency were also found to be significant for the product ash response. A careful examination of Equation 2 indicates that deck vibration frequency may play a greater role in affecting product ash than fines percentage in the feed. Even if the percentage of fines in the feed is lowered, increasing deck vibration frequency may result in a lower product ash. In addition, the negative impact of lowered deck vibration frequency can be offset by increasing the percentage of fines in the feed. Although, interaction of deck vibration frequency and feeder frequency (i.e., feed rate) also plays a significant role in affecting product ash, the negative impact of lowering bed frequency cannot be completely offset by increasing feed rate.

Equation 3 reveals that separation efficiency, which is described as the difference between combustible recovery and ash recovery, is a first order function of all three process variables. It increases by increasing the percentage of fines in the feed and the deck vibration frequency, whereas it decreases by increasing the feeder frequency or feed rate to the FGX deck. Both fine content of feed coal and deck vibration frequency aid in improving fluidization characteristics of the coal bed and thus improve separation efficiency. On the other hand, increasing feed rate renders proper stratification of the coal bed increasingly difficult and thus results in poorer separation efficiency.

Equation 4 describes the sulfur rejection performance as a function all three process variables adjusted during this test program. It is evident from the largest positive coefficient that deck vibration frequency (C) plays the most significant role in affecting sulfur rejection performance achievable from the FGX Dry Separator. Higher vibration frequency causes better stratification of high-density coal pyrite and low-density clean coal particles on the deck resulting in higher sulfur rejection. The negative impact of increasing feed rate, as indicated by the negative coefficient for feeder frequency (B), on sulfur rejection performance can be offset by increasing deck vibration frequency and/or the percentage of fines in the feed coal.

Task 2.2: Investigation of FGX Dry Separator's Fine Coal Cleaning Performance: Another primary objective of this study was investigating the suitability of the FGX Dry Separator for cleaning fine (-4-mesh) coal. Additional -4-mesh coal was prepared from the rotary breaker product by screening another two tons of coal. This coal was processed in the FGX Dry Separator with all key process variables set based on previous testing to obtain optimum cleaning performance. Ash rejection versus combustible recovery for these tests is shown in Figure 5 indicating that 90% combustible recovery could be achieved when ash rejection is 30%; however, as the feed washability curve indicates, FGX fine coal cleaning performance has to significantly improve to be considered effective.

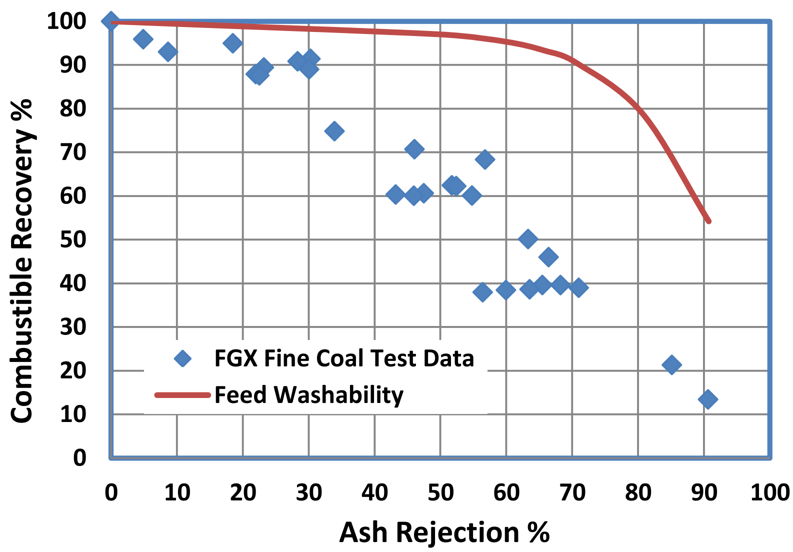

Figure 5: Ash rejection vs. combustible recovery for fine (-4-mesh) coal cleaning with the FGX Dry Separator.

To better understand fluidization characteristics for a bed consisting only of fine coal, a laboratory scale fluidization chamber, as shown in Figure 6, was designed and fabricated at SIUC to simulate that condition and determine the optimum level of fluidization force. This fluidization chamber was made of an 8-inch tall plexiglass tube having several ports at measured distances along the height of the tube, which are connected to a U-tube manometer to measure the pressure drop across the height of the column bed. The fine coal column bed was connected to a compressed air supply line using an air flow meter, a valve, and a pressure gage. Fine (-4-mesh) coal samples were loaded into the column at different heights and the pressure drop across the column was monitored while the air flow rate into the bed was gradually increased until a bubbly zone was visually observed in the fine coal bed.

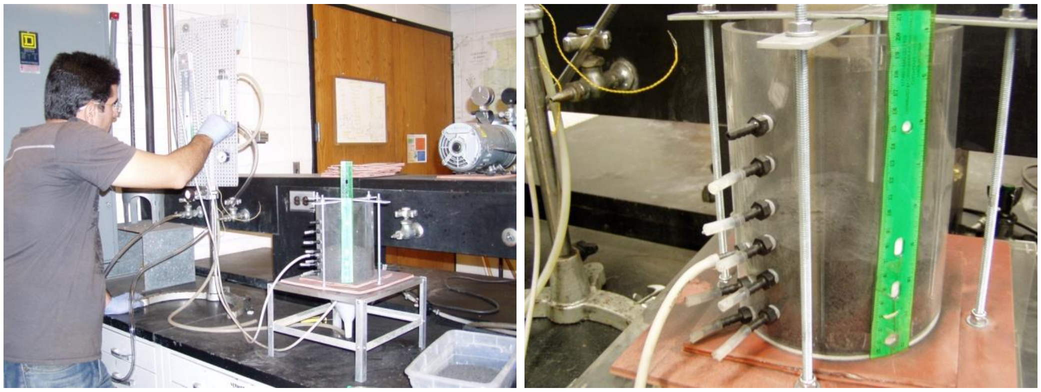

Figure 6: Laboratory-scale fluidization chamber fabricated at SIUC.

Figure 7 shows the pressure drop across the bed for a 4-inch bed height as a function of increasing superficial air flow rate. As indicated, increasing the air flow rate increases the pressure drop across the fluidized bed to a maximum point after which it fluctuates at a level below the maximum. It can be inferred from these experiments that the peak superficial air flow rate (approximately 60 ft/min) is the optimum air flow velocity required to fluidize a 4-inch high bed of this fine coal sample.

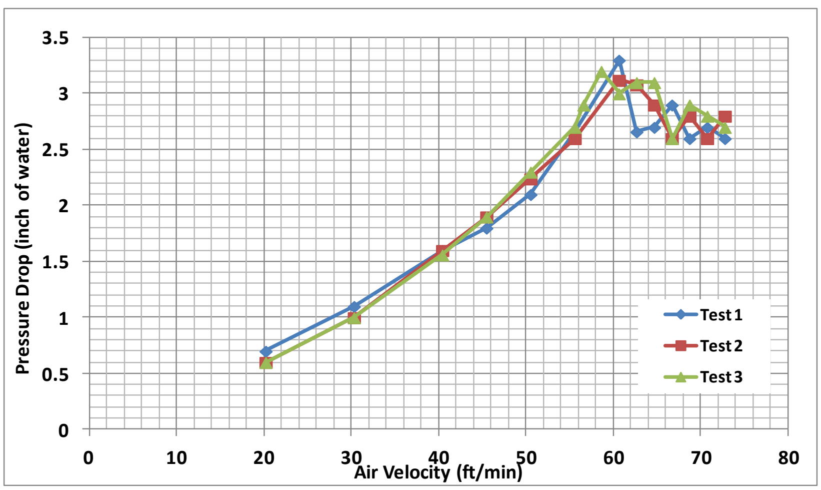

Figure 7: Air flow velocity vs. pressure drop for a 4-inch bed height in the laboratory-scale fluidization chamber.

With 5-mm perforations in the separating deck, the FGX Dry Separator as manufactured was unsuitable for fine coal cleaning. Based on fluidization results shown in Figure 7, the FGX Dry Separator's deck and fluidization system were modified to approach experimental conditions more suitable for fine coal cleaning. After several stages of modification, a screen and fluidization system were found that achieved very good separation efficiency for cleaning fine coal as summarized in Table 4. More than 90% combustible recovery was achieved while ash and sulfur rejection were more than 40%

and 26%, respectively. Comparative data plotted in Figure 8 indicates the distinct superiority of the cleaning performance achieved with the new air table. These results were verified using a second fine coal sample, as shown in Table 5. This new "air table" will require further research to fully develop.

Table 4: Results with new fine coal separating deck.

Test No.	Feed Ash (%)	P* Ash (%)	M* Ash (%)	T* Ash (%)	Clean Coal Yield (P+M) (%)	CR** (P+M) (%)	AR** (T) (%)	SR** (T) (%)
1	29.19	16.85	21.67	65.89	81.84	91.25	40.98	26.98
2	32.75	17.94	23.57	65.67	77.16	88.34	45.79	31.98
3	25.58	13.53	18.87	66.64	83.94	92.80	41.83	17.56
4	25.00	17.95	-	56.62	81.78	89.46	41.27	18.07

***: P**=product; **M**=middlings; **T**=tailings
****: CR=**combustible recovery; **AR=**ash rejection; **SR=**sulfur rejection

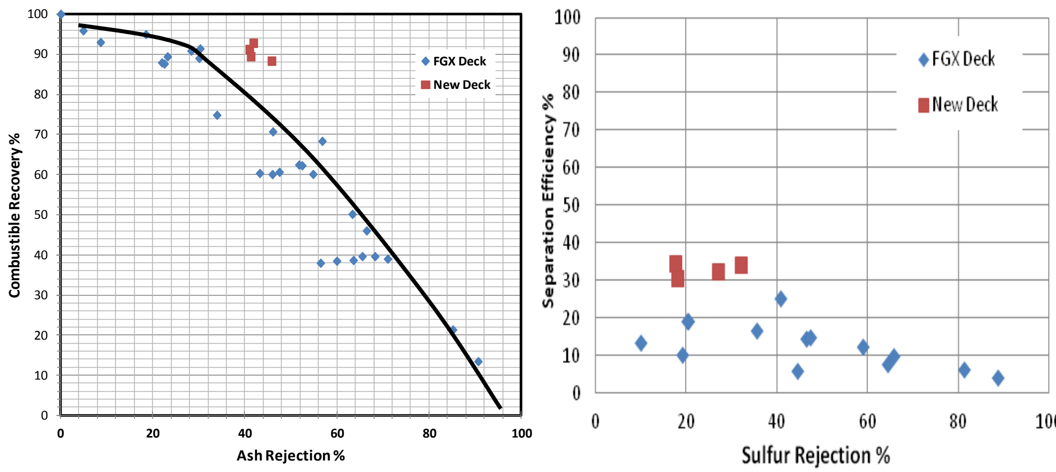

Figure 8: Fine coal cleaning performance of FGX deck and new deck.

Table 5: Results with new fine coal deck and 2nd Illinois coal sample.

Test No.	Feed Ash (%)	P* Ash (%)	M* Ash (%)	T* Ash (%)	Clean Coal Yield P+M) (%)	CR** (P+M) (%)	AR** (T) (%)
1	28.98	17.39	19.03	66.16	77.85	89.44	50.57
2	27.55	12.67	17.66	44.66	62.06	71.02	61.51
3	25.27	16.73	21.08	52.27	82.47	88.81	36.25
4	26.01	13.56	23.75	62.59	85.48	92.66	34.93
5	25.06	13.86	24.74	63.86	87.10	93.78	32.86
6	25.67	17.33	21.74	59.09	85.23	91.87	34.01

***: P**=product; **M**=middlings; **T**=tailings
****: CR=**combustible recovery; **AR=**ash rejection

Task 3: Evaluation of Two-stage FGX Cleaning with Intermediate Crushing

In the previous study (Mohanty, 2010), the FGX Dry Separator was found to lose a small proportion of clean coal to the middlings stream and, in cases of relatively difficult to clean coal, to the tailings stream. It was hypothesized that the middlings product will most likely have difficult cleaning characteristics. Hence, separating clean coal from rock in the middlings product would be feasible only after it goes through a size reduction step to improve ash liberation characteristics. This hypothesis was experimentally verified using a roll crusher at the Gundlach Manufacturing Company located in Bellville, IL to prepare crushed middlings samples for second stage FGX cleaning.

Based on FGX cleaning results obtained in Task 2.1, process parameters were set at optimum levels of 40% fines, 35 Hz feeder frequency, and 55 Hz bed frequency for first stage FGX cleaning. This produced a tailings stream with approximately 79% ash, requiring no further cleaning. Therefore, it was decided to do second-stage FGX cleaning of only crushed middlings product and several barrels of middlings sample were crushed into two top sizes. Particle size distributions of the original middlings (3-inch top size) and the two crushed middlings (1-inch and 1.5-inch top size) samples are shown in Figure 9 with d_{80} sizes of approximately 1.1, 0.77, and 0.37 inches, respectively.

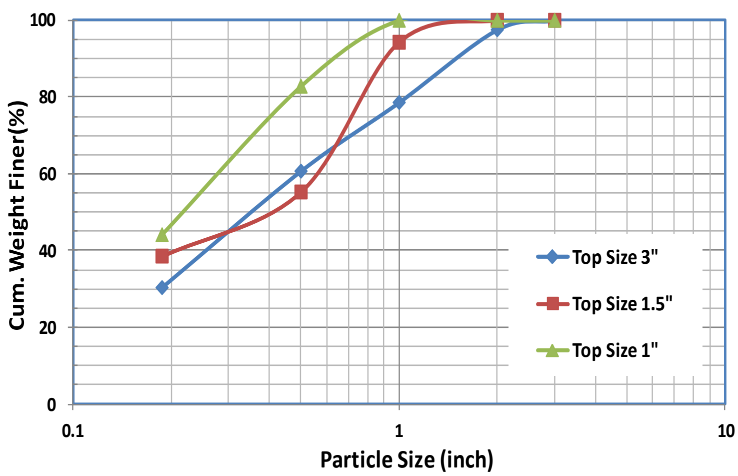

Figure 4: Size distributions of original and crushed middlings product.

Second-stage FGX cleaning was conducted separately for all three samples with results shown in Figure 10. They indicate that the original middlings sample and the middlings sample crushed to 1.5-inch top size had similar cleaning characteristics; however, significant improvement in cleaning characteristics was observed for the middlings sample crushed to 1-inch top size. At a high combustive recovery of nearly 90%, ash rejection improved from about 20% to nearly 37%.

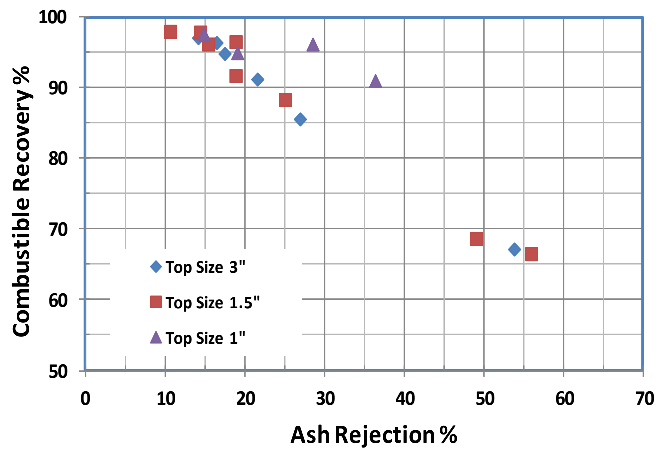

Figure 10: Results of second-stage FGX cleaning of middlings products.

Predictably, the -4-mesh size fraction of the original middlings sample would change significantly upon crushing increasing from 30% fines in the uncrushed sample to 38% fines when crushed to 1.5-inch top size and 44% when crushed to 1-inch top size. It was desired to isolate the positive effect of increased fines content in middlings product crushed to different top sizes that was confounded in coarse coal cleaning results presented in Figure 10. Therefore, another series of FGX tests was conducted to maintain fines content during second-stage cleaning of 1-inch top size middlings at the original middlings fine content level of nearly 30%. Results presented in Figures 11 and 12 clearly indicate that the improvement in FGX cleaning performance is primarily due to improved liberation caused by intermediate crushing. It is believed that much better cleaning performance could be obtained from the overall dry separation plant flowsheet by crushing first-stage FGX middlings to an even lower top size of 1/4-inch before cleaning with the new air table developed for fine coal cleaning.

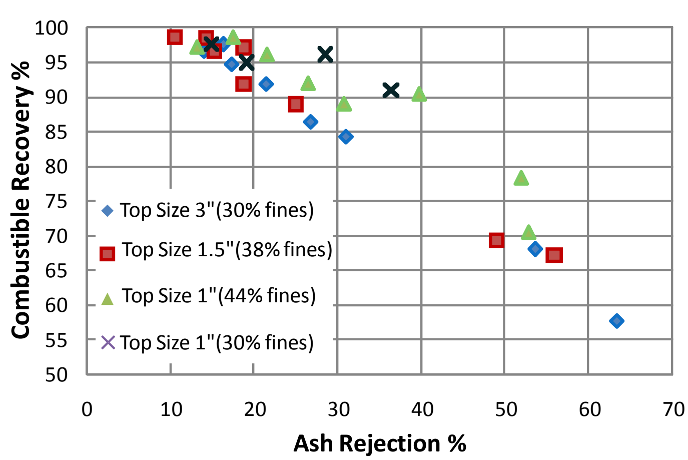

Figure 11: Results of second-stage FGX cleaning of original first-stage middlings and crushed middlings products.

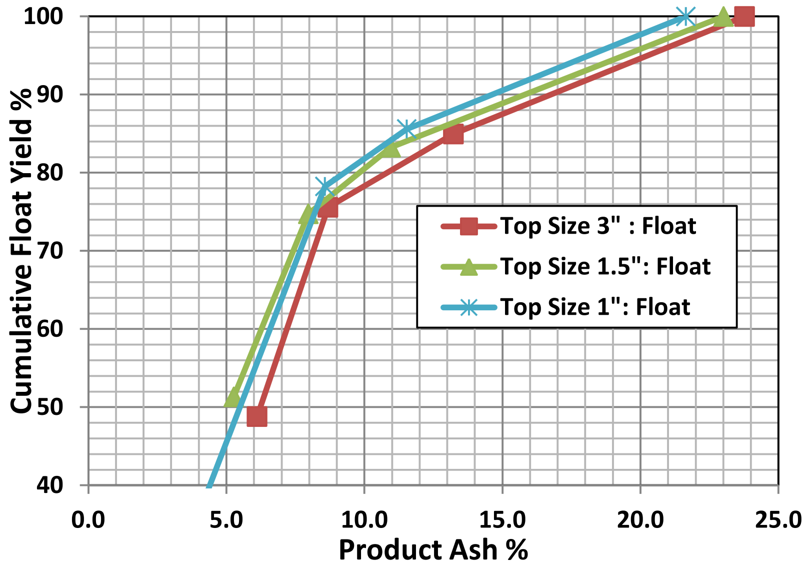

Figure 12: Improved liberation characteristics of middlings sample with intermediate crushing.

Task 4: Fully Integrated Dry Separation Coal Preparation Plant Flowsheet

Based on results from the first three tasks, a completely integrated flowsheet was developed to determine overall performance of a dry separation preparation plant in terms of plant yield and clean coal product quality. The circuit configuration had to be modified from what was originally proposed based on FGX fine coal cleaning results. The modified dry separation plant flowsheet includes a rotary breaker and FGX Dry Separator for coarse coal cleaning and a new air table for fine coal cleaning, as shown in Figure 13.

Experimental results were used to determine typical mass flow rates and corresponding ash and sulfur assays of each stream for the dry separation plant flowsheet required to clean 100 tph of ROM Illinois No. 6 seam coal. The overall strategy was to obtain a relatively large middlings stream from FGX coarse coal cleaning and crush it to improve liberation characteristics before cleaning it with an air table designed to clean -1/4-inch coal. The performance of the air table shown in Figure 13 is based on results obtained for a new deck tested in the FGX Dry Separator; however, better cleaning performance is expected from a new air table suitably designed for cleaning fine coal. For a ROM Illinois No. 6 coal having a feed ash of 33.4%, an overall plant yield of 68.8% would be achieved with a clean coal ash of 16%. Sulfur content would be lowered from 3.73 to 3.12% by rejecting more than 50% of the sulfur present in the feed coal. In comparison, the current wet coal preparation plant operating at the Prairie Eagle Mine provides a clean coal yield in the range of 60 to 67% at a product ash of ~9.5% (on a dry basis) and a product sulfur of ~3.25% (Stanley, 2012). The moisture content of the current plant product is ~13.5%, whereas the moisture content of the dry separation plant product would be very close to the inherent moisture content of the coal, which is about 8% for Prairie Eagle's Illinois No. 6 coal. It may be noted that although the dry separation plant product ash of 16% may appear high in comparison the clean coal produced by the conventional wet plant, the heating value, which is directly related to the arithmetic sum of ash and moisture content, would be nearly equal for both clean coal products.

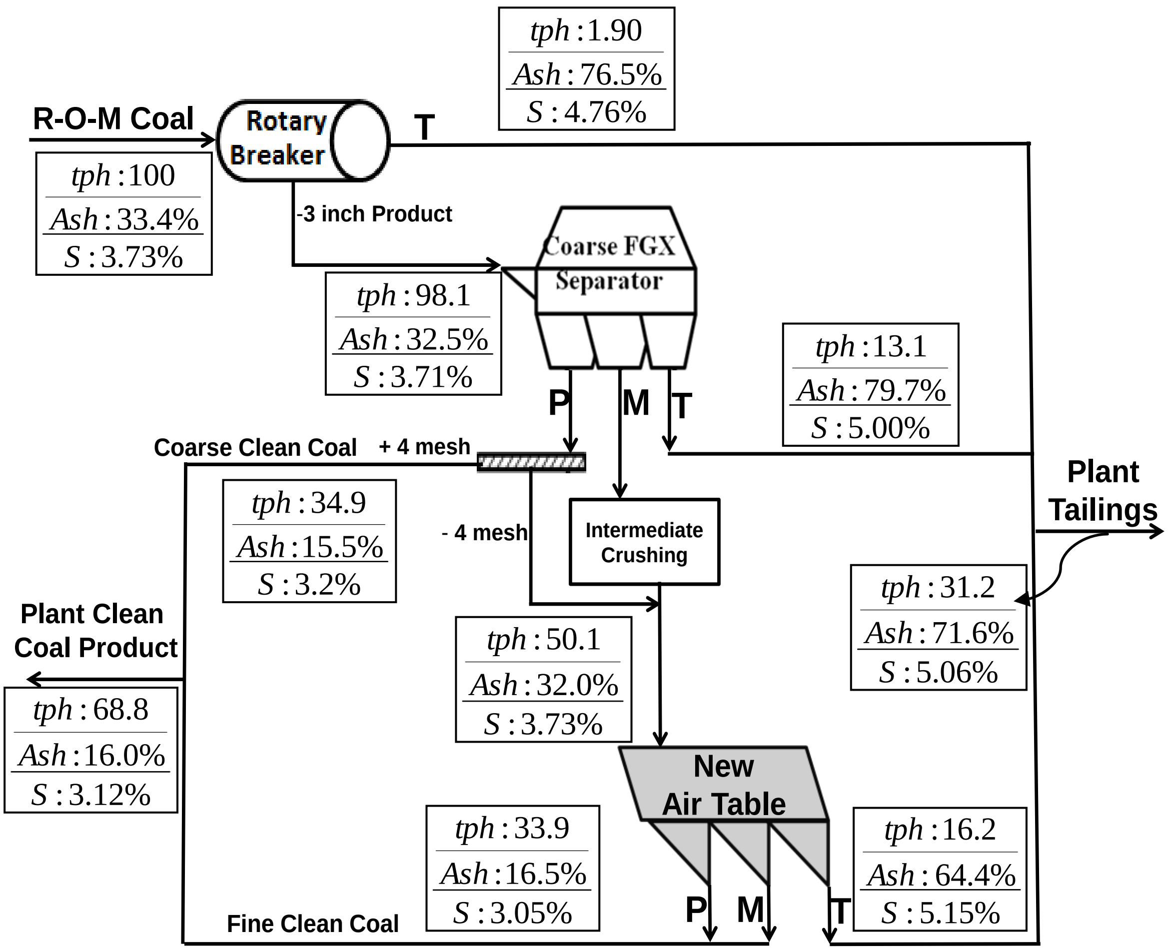

Figure 13: Dry separation flowsheet for cleaning Illinois Basin coal.

Task 5: Economic Analysis

A preliminary economic analysis was conducted to estimate coal cleaning costs on a per ton basis for Illinois coal using the dry preparation plant flowsheet developed in this study. This economic analysis is based on costs incurred in recent commercial FGX installations, including the one in Illinois (see Figure 14) and assumed costs for a new fine coal air table technology shown in the proposed plant flowsheet (Figure 13) but yet to be developed.

Figure 14: First commercial installation of the FGX Dry Separator in Illinois by the Eagle River Coal Company.

Capital Cost:

Rotary breaker (9' x 15'):	$400,000	(Burns, 2012)
FGX-12 (120 tph capacity):	$550,000	(Parekh, 2012)
Crusher (Two stage, four roll):	$175,000	(Hamby, 2012)
Fine coal air table:	$ 550,000	(Assumed)
Total Capital Cost:	$1,675,000	

Using a factor of 2 (which is common), total capital and installation cost (CAPEX) can be estimated to be $3.35 million. Given a capital recovery factor of 0.1339 (12% rate of return and 20-year plant life), annualized CAPEX is estimated to be $448,565.

Operating and Maintenance Cost:

Total horsepower (HP) requirements for the Model FGX-12 Dry Separator are 432 HP including 335 HP for the blower fan motor, 50 HP for the draft fan motor, 30 HP for two vibratory motors, and 10 HP for the air compressor motor. The remaining horsepower is needed for conveyor belt motors. The Model FGX-12 Dry Separator is expected to operate 120 hours per week for 50 weeks per year (assuming 6000 work-hour/year) with two operators paid $25 per hour. Maintenance costs include regular deck rebuilds and replacing rubber liners. These estimates enable determination of the following operating and maintenance costs:

Cost	Per Week	Per Month	Annual
Energy		$9,000	$103,500
Labor	$6,000		$300,000
Maintenance			$ 10,000
Operating and maintenance costs for the FGX Unit			$413,500

In the absence of actual operating cost data for the new air table, which is yet to be built, similar energy and maintenance costs as those of FGX are assumed. Considering just one operator for the new air table, annual operating costs are estimated to be $263,500. The operating cost for the two stage double roll crusher that will be required for reducing the top size of the middlings stream to 1/4 -inch is ~$0.04/ton (Hamby, 2012). As indicated in the plant flowsheet, the crusher will have to crush the middlings material of ~50 tph; this results in an annual operating cost for the crusher of $12000 (i.e., 50 ton/hour x 6000 hour/year x $0.04/ton).

The rotary breaker's operating cost is mostly the energy for operating its 50 HP (~37 kW) motor. Therefore, annual operating costs for the rotary breaker are estimated to be ~$16000 (based on 7¢/kWH).

Thus, total annual operating costs for the entire plant would be:
$413,400+$263,500+$12000+$16000=$705,000

Therefore, total annual ownership and operating costs are:
$448,565+$705,000=$1,153,565.

This translates to $1.94/ton of raw coal and $2.81/ton of clean coal product. Operating cost alone would be $1.18 and $1.71 per ton of raw coal and clean coal, respectively.

CONCLUSIONS AND RECOMMENDATIONS

A dry coal preparation plant flowsheet has been proposed for cleaning the entire ROM coal through empirical studies with individual unit operations. The flowsheet consists of a rotary breaker to achieve preliminary de-shaling of ROM coal, a FGX Dry Separator for cleaning coarse (+4-mesh) coal, and a new air table for cleaning fine (-4-mesh) coal. Key findings of this study are summarized as follows:

Conclusions

1. A rotary breaker operating at a nearby mine cleaning Illinois No. 6 seam coal was found to reject 1.9% of the ROM feed; the ash content of the rejected material was nearly 77%. Approximately 7.94% of the reject stream constituted low-ash coal having an average ash content of 11.20%. However, this clean coal loss is a very small percentage (0.15%) of the rotary breaker feed.

2. An experimental program using Central Composite Design (CCD) and response surface methodology data analysis techniques validated that the percentage of fine material (-4-mesh) in the feed has a significant effect on all four process responses (i.e., tailings ash, product ash, separation efficiency, and sulfur rejection) studied during this investigation. The optimal fines percentage for achieving better coarse coal cleaning performance from the FGX Dry Separator was found to be nearly 28%.

3. Second-stage FGX cleaning achieved better separation performance when the middlings sample was crushed to 1-inch top size prior to cleaning. At 90% combustible recovery, ash rejection improved from about 20% to nearly 37%. Testing showed that this performance enhancement was caused primarily by improvements in liberation characteristics of the middlings product due to intermediate crushing.

4. Extensive tests conducted to evaluate the suitability of the FGX Dry Separator for fine coal cleaning with even a modified air flow system provided only marginal cleaning for coal finer than 5-6-mm in size. Therefore, it was concluded that the FGX Dry Separator is not suitable for providing effective cleaning performance for fine coal and pursuit of a new air table designed to clean fine coal continues.

5. A laboratory-scale fluidization chamber was fabricated at SIUC for better understanding of fluidization characteristics of fine coal. This study resulted in developing a new separating deck for the FGX Dry Separator at SIUC and modifying the FGX Dry Separator’s air flow system to be suitable for fine coal cleaning. Using this system, ash rejection increased up to 45% at a combustible recovery of 90% for the same fine coal as was tested before. For a second coal sample, ash rejection above 50% was achieved at 90% combustible recovery. It is believed that a new air table designed and built incorporating these findings would most certainly help in achieving even better ash and sulfur rejection performance for fine coal cleaning.

6. Based on the actual test results obtained from the individual dry separation unit operations comprising the dry separation plant flowsheet, it is projected that clean coal yield of 68.8% could be achieved at a product ash content of 16% (on a dry basis) and sulfur content of 3.12% (dry basis) by cleaning Knight Hawk Coal’s Illinois No. 6 coal having 33.4% feed ash and 3.73% sulfur. In comparison, the current wet coal preparation plant serving the Prairie Eagle Mine provides a clean coal yield in the range of 60 to 67% at a product ash of ~9.5% (on a dry basis) and a product sulfur of ~3.25% (dry basis). The moisture content of the current plant product is ~13.5%, whereas the moisture content of the dry separation plant product would be very close to the inherent moisture content of Prairie Eagle coal, which is about 8%. It may be noted that although the dry separation plant product ash content of 16% may appear high in comparison to that of the clean coal produced by the conventional wet plant, the heating value, which is directly related to the arithmetic sum of ash and moisture content, would be nearly equal for both clean coal products.

7. A preliminary economic analysis of the entire dry separation plant flowsheet resulted

in an estimated ownership and operating cost of $1.94 and $2.81, per ton of ROM coal and per ton of clean coal product, respectively. The operating cost alone would be $1.18 and $1.71 per ton of raw coal and clean coal, respectively. These cost figures made two important assumptions: (a) the circuit installation cost is an additional 100% of the equipment capital cost; (b) a new air table's capital and operating cost are likely to be nearly similar to that of the FGX Dry Separator.

Recommendations

1. Based on the findings of this study, a prototype air table should be built to achieve effective fine coal cleaning. Its design parameters, including air flow system, deck vibration amplitude, and deck vibration direction should be fine-tuned based on additional fundamental and empirical studies. A computational fluid dynamics (CFD) model is already being formulated at SIUC to aid in developing a highly effective fine coal cleaning air table.

2. Efficient dry screening systems need to be evaluated and included in the dry separation plant flowsheet for improving the efficiency of fine coal cleaning.

3. The complete dry separation plant flowsheet needs to be demonstrated at a plant site for its near-term commercialization in Illinois coal mines.

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