UPGRADING LOW RANK COAL USING A DRY, DENSITY-BASED SEPARATOR TECHNOLOGY

T. Ghosh[(1)], R.Q. Honaker[(1)], D. Patil[(2)], B.K. Parekh[(3)*]

[(1)]Department of Mining Engineering, University of Kentucky, Lexington, Kentucky, USA, rick.honaker@uky.edu
[(2)]Alden Resources, Corbin, Kentucky, USA, dpatil@aldenresources.com
[(3)] FGX Technologies, Lexington, Kentucky USA,

ABSTRACT

Low rank coal such as the coal in the Powder River Basin (PRB) is typically direct shipped without any need for upgrading. Due to the lack of on-site processing capabilities, coal that is mixed with out-of-seam dilution during the mining process is typically left in the mine pit. In some cases, the loss could amount to 5% of the total reserve. Research conducted on laboratory and pilot scale pneumatic air table separators indicates that sufficient upgrading can be achieved on the +1mm fraction of the reject material to meet typical end-user specifications. Low rank coals are especially susceptible to upgrading by density-based processes due its naturally lower density relative to higher rank coals. For example, a PRB coal containing 26% feed ash was reduced to 7% ash content with a combustible recovery of 83% on a dry basis from a coal source that was reject from the mining process. Partition curve data revealed the achievement of relatively low Ep values in the range of 0.12 to 0.22 with separation densities between 1.58 and 1.88 gm/cm^3, respectively. Effective separations were achieved using air table separators for particle sizes larger than 1 mm.

Keywords: Low Rank Coal, Dry Cleaning, Air Tables, Efficiency.

1. INTRODUCTION

The cleaning of low rank coal is of significant interest worldwide due to overall demand from reserves that contain partings and the desire to maximize reserve recovery from deposits from which a portion of the coal is diluted with out-of-seam material during extraction. An example is the large reserve of sub-bituminous coal in Powder River Basin (PRB) of the U.S. The typical PRB coal seams are 30 meters thick with the presence of significant partings as the seam dips downward toward the bottom of the basin. Extraction of PRB coal results in a large amount of out-of-seam material intermixing with a significant portion of the coal. Since no cleaning facilities are currently utilized, the diluted coal along with any coal contaminated by parting material is placed into the mine pit as reject.

The upgrading of low rank coal by a density-based separator is more favorable than the performances achieved with high rank coals due to the high inherent moisture content which range from approximately 20% to 30%. For example, the specific gravity of a typical 1.30 gravity block of bituminous coal decreases to 1.21 when 25% moisture is added which would approximate the specific gravity of high grade sub-bituminous coal. The specific gravity of the out-of-seam or parting material is typically greater than 2.0. Dry air-based density separation is a more favorable option for the low-rank coal for a number of reasons including its lower overall market value and the relative costs of wet cleaning facilities and the scarcity of water in locations where low rank coals can be economically extracted.

Worldwide interest in dry coal cleaning has significantly increased mainly due the need to process materials in arid locations. While the wet cleaning processes remain the most efficient for cleaning coarse to ultrafine particles, dry processing is advantageous in eliminating or minimizing water requirements and avoiding the environmental impacts caused by process water and fine waste storage while also offering a significant reduction in capital and operating expenditure. Honaker et al. (2008) demonstrated the significant economic benefits of removing small amounts of rock from a low-ash run-of-mine coal using the dry separator with an additional applicability in de-shaling run-of-mine coals mined from thin seams having significant out-of-seam dilution.

Dry coal cleaning technologies were prevalent in the industry throughout the early to middle twentieth century. Major innovations and development of dry, density based separators occurred during the 20 year period of 1910 and 1930.The U.S. coal industry processed a significant amount of coal until about 1968 when production peaked at 25.4 million tons annually (McCulloch et. al., 1968). Pennsylvania had the distinction of operating the largest dry cleaning plant with 14 units processing about 1400 tph of coal. By 1990, most of the dry cleaning plants were either closed down or their capacities severely stunted due to federal dust exposure regulations which required the use of a significant amount of water prior to the processing plant to suppress dust.

- Corresponding author “bhuparekh@gmail.com”

Air table technologies originally developed and patented in the 1920's have been recently redesigned and equipped with modern technologies including automation systems that provide a means of efficient separation performance control. Air-based separation units utilize an upward flow of air to create a fluidized bed of high-density particles. Coal particles are not able to penetrate through the bed and thus float on top whereas high-density, high-ash content particles move through the bed. A vibrating table provides a mechanism to separate the coal floating on top of the bed from the reject material that forms the lower part of the bed. Honaker and Patil (2007) and Luo et al. (2007) reported on the application of air table concentrators for cleaning coal. The modern air-based density separators are efficient in beneficiating coal between a size range of 75 mm to 6 mm with an effective size ratio around 4:1. Particle sizes smaller than 6 mm display a higher probability of reporting to the product stream irrespective of their relative density distribution.

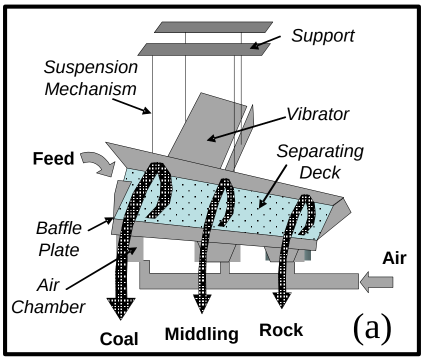
A mobile pilot scale air table commercially known as the FGX separator was evaluated on-site for cleaning PRB coal coarser than 6 mm size range. The study was followed by a laboratory experimental program using a modified laboratory Bratney table to evaluate the potential of treating coal as fine as 1 mm. This publication presents and discusses the results of both studies which involved the upgrading of low rank coal from the Powder River Basin.

2. EXPERIMENTAL

2.1 Process Description

The dry density separator employs the beneficiation principles of an air table concentrator and an autogeneous medium. The feed to the system is introduced into a feed hopper from which the flow is controlled using a vibrating feeder. The separation process generates multiple products of varying grades. Industrial and pilot scale units are equipped with dust collection systems to clean the recycled air and to remove about 90% of the re-circulating dust from the system. The separating compartment consists of a deck, vibrator, air chamber and hanging mechanism. A centrifugal fan provides air that passes through holes on the deck surface at a rate sufficient to transport and fluidize the light coal particles. The angle of the deck and direction of the air flow drives the light, fluidized particles toward the front of the table and discharge over an adjustable lip. The deck width is reduced from the feed end to the final refuse discharge end.

Introduction of the feed coal into the separation chamber is followed by the formation of a particle laden bed of certain depth (Figure 1). The separating bed is comprised of a bed face, a back plate, lattice bars and discharge dampers. The vertical and horizontal angles of inclination of the bed can be altered by the help of mechanical or electronic control systems. 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 end of the table. 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.



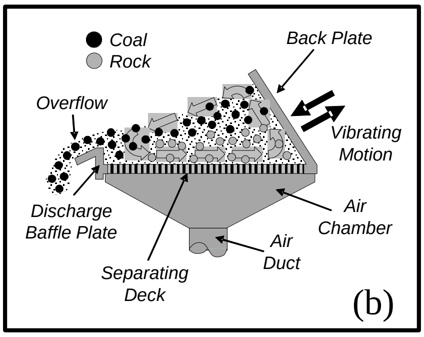


Figure 1. Mechanisms and separation principles of the FGX separator showing (a) the separation chamber and (b) particle motion and separation mechanism (Honaker et al., 2007).

The test program using the FGX unit focused on the capability of upgrading particles coarser than 6mm. To evaluate the potential for achieving effective air table separations to a particle size of 1 mm, a modified laboratory scale unit of the Bratney air table was utilized. Although the table configuration is different than the FGX system, the principles of operation are identical. Figure 2 shows the simplified particle paths and the sample collection points A, B, C, D and E for each laboratory test.

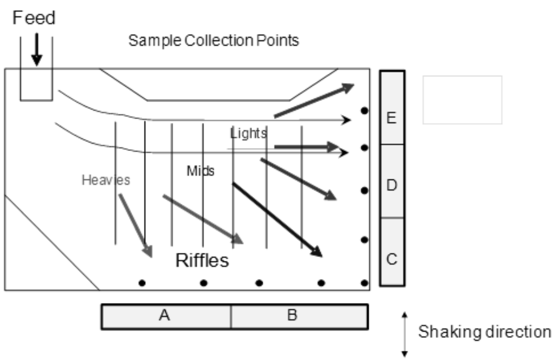


Figure 2. Schematic of the laboratory air table (top view).

2.2 Test Program Description

2.2.1 On-Site Pilot Plant Test Program

The on-site pilot scale tests were conducted using a 5 t/h FGX Separator unit. The feed was screened at 6 mm using a mobile vibrating screen to restrict the amount of moisture and ultrafine particles. A statistically designed test program was performed to optimize performance by manipulating the values for table vibrating frequency, the longitudinal table slope and the fluidization air rate. The total number of pilot-scale tests was 15. A total of six sample splits, each 40 cm apart, were collected along the length of the table during each test, thereby providing the data needed for a yield versus product ash relationship from each test. The performance target was to produce clean coal in the plus 6 mm fraction containing around 6 % to 8 % ash from an average feed ash content of 19.47 %. The longitudinal slope angle was varied between 0^0 and 1.5^0 with the cross table slope kept constant at 8.5^0. The blower frequency range was between 50 hz and 60 hz with the table vibrating frequency being evaluated for a range of 40 hz to 50 hz.

2.2.2 Laboratory Test Program

Powder River Basin (PRB) coal obtained for the purpose of the laboratory test work was crushed and screened to prepare a 6 x 1 mm feed. The ash content of the feed was around 26%. Upgrading of the 6 x 1 mm material using the modified Bratney laboratory air table separator was evaluated by performing a controlled test program involving the optimization of the operating parameter values including longitudinal and transverse angles, table frequency and air flow rate. A 3-level Box-Behnken design experimental program was used for this purpose in which the central values were considered as well as the interactive effects of the significant parameters (Table 1). The total number of tests conducted was 26. The test results were used to develop empirical models describing the performance response variables as a function of the operating parameter values and their associated interactions. Timed product samples were collected for each test. The samples were weighed to determine mass yield and analyzed for ash and heating value content to quantify the amount of upgrading and energy recovery. Subsequent tests were run under optimized conditions to maximize the product yield at a given product ash.

Table 1. Laboratory air table parameters and their levels used in the Box-Behnken test program.

Parameter	Level		
	-1	0	+1
Blower Frequency (Hz)	30	40	50
Table Frequency (Hz)	30	35	40
Longitudinal Angle (°)	1	1.5	2
Transverse Angle (°)	4	6	8

3. RESULTS AND DISCUSSION

3.1 On-Site Pilot-Scale Tests

A typical separation performance achieved when treating the 75 x 6 mm PRB coal is shown in Figure 3. The separation obtained across the length of the table indicates the substantial potential for achieving significant upgrading when treating low rank coal. At a flow rate of 3.09 t/h, the majority of the feed reported to split 1 (almost 45%) with an ash content of 6.07% which meets market specifications. The ash content was nearly equal in split 2 and slightly higher in split 3. As such, the data suggests that a product meeting contract grade requirements is achievable by combining splits 1 through 3 which contains 82.2% of the total feed.

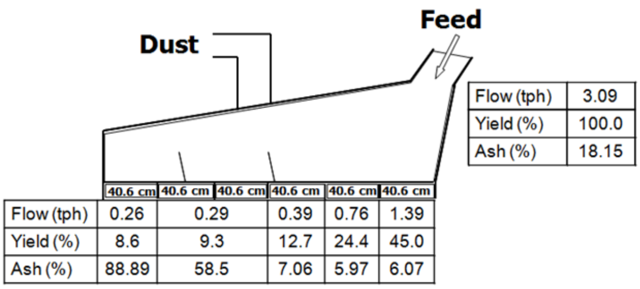


Figure 3. The separation performance achieved across the length of the table when treating 75 x 6 mm PRB coal.

Optimum performances are shown in Figure 4 in which the cumulative mass yield from the far right to left of the table front edge is plotted versus the corresponding cumulative product ash content. All tests generated a product containing less than 7% ash with mass yield values around 80%. The optimal test performance provided a product ash content of 6.19% with a yield of 82.1% from a feed having 19.47% ash.

The particle size-by-size performances achieved under the optimum conditions show that significant ash reductions were achieved for all size fractions including the particles finer than 6 mm (Figure 5a). The data also shows very high ash contents in Stream 5 which would represent the majority of the reject stream. The majority of the mass reported in Stream 1 as shown in Figure 5b which contains the lowest ash content material.

3.2 Laboratory Test Program

To evaluate the potential of an air table to upgrade 6 x 1 mm coal, a parametric test program was performed based on a 3-level Box-Behnken design with a constant feed rate of 204 kg/hr. A total of 26 tests were conducted as part of the test program and 6 samples collected for each test. Figure 6 depicts typical sets of data collected for each experiment plotted in the form of cumulative ash versus cumulative yield. The analysis of experimental results shows that it is possible to achieve a product containing as low as 7.0% ash with 55% product yield. A further increase in product yield up to 75% slightly increases the product ash to 8.5%.

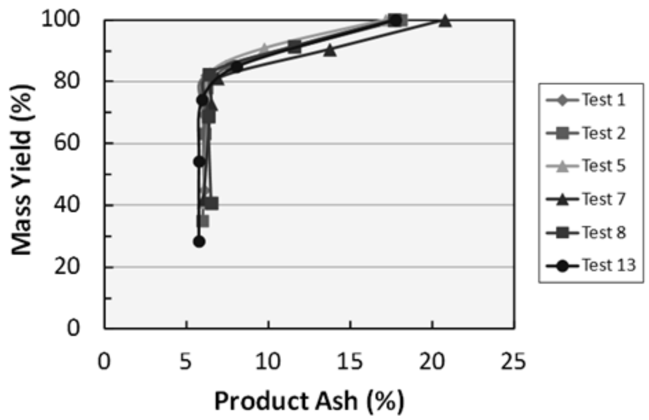


Figure 4. Optimum separation performances achieved from the processing of 75 x 6 mm sub-bituminous coal using a 5 t/h FGX separator.

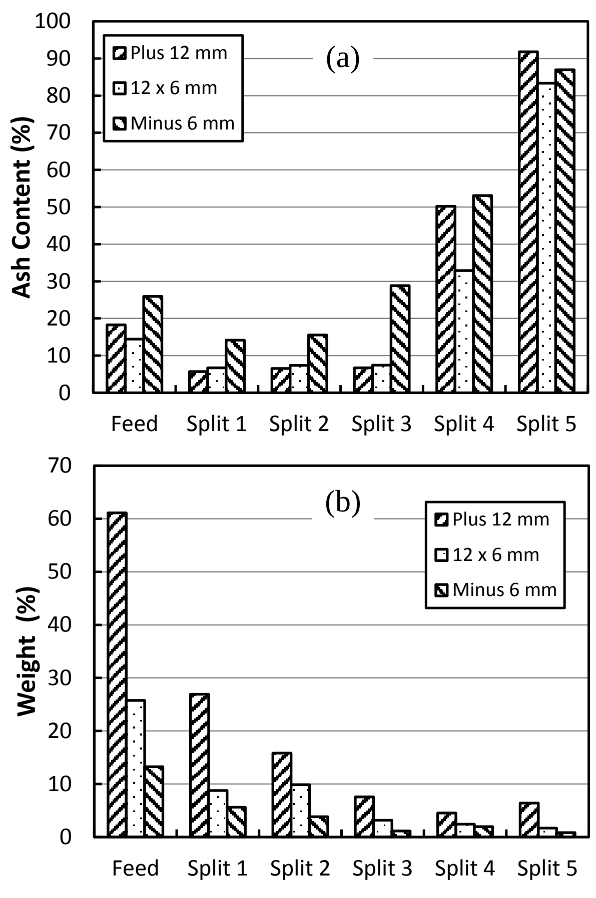


Figure 5. Particle size-by-size performance obtained when operating under optimum conditions on the basis of (a) ash content and (b) weight percent along the table front edge.

The experiment data obtained over a range of test conditions found variations in product ash content from 7 % to 17 %. This clearly indicates the ability of the technology to provide clean coal meeting a range of market specifications. The data set was analyzed using commercially available statistical analysis software. The following empirical models were generated describing product yield and ash content as a function of the operating parameter values:

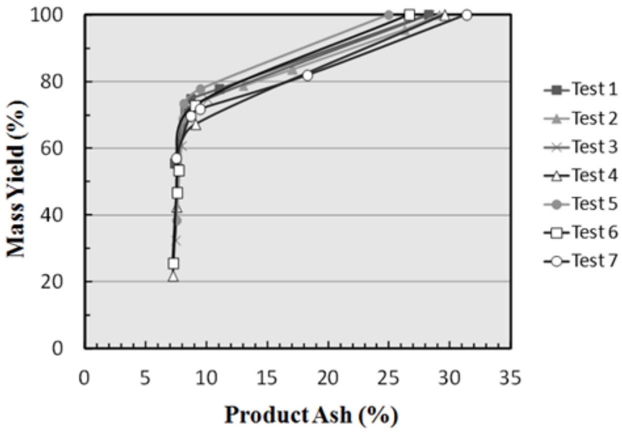


Figure 6. Separation performances obtained from cleaning 6 x 1 mm sub-bituminous coal using a laboratory air table.

$$Product\ Yield(\%) = 97.13 + 1.39(Fan\ Frequency) - 2.57(Table\ Frequency) - 16.33(Longitudinal\ Angle) + 4.67(Transverse\ Angle); \quad (1)$$

$$Product\ Ash(\%) = -25.54 + 0.15(Fan\ Frequency) + 0.72(Table\ Frequency) - 1.81(Longitudinal\ Angle) + 7.68(Transverse\ Angle) - 0.19(Table\ Frequency * Transverse\ Angle). \quad (2)$$

The product yield and product ash values increase with decrease in longitudinal angle due to the augmented slope towards the product discharge end. During the testing, it was observed that, with fan frequency controlling the air-flow rate, the low density coal particles were easily lifted by the upward air medium and moved freely towards product end. The higher flow rates coupled with an increase in the longitudinal angle helps to normalize the fluidized bed formation thus maximizing combustible recovery and yield (Figure 7). Moreover, the table is designed in such a way that the section of the table where light particles travel to the discharge end comes closer to the air blower outlet which may increase the airflow rate thus creating a greater amount of fluidization. Only particles light enough to float in the air travel to the discharge end, hence reducing the product ash and yield as the longitudinal slope is increased. The introduction of particle feed at a steady rate at the feed end results in the dampening of airflow at the feed end, which directly affects the flow rate at the discharge end.

An increase in the transverse angle increased the product yield while increasing the product ash. This could be attributed to the higher flow rate of solids to the product end, as it becomes increasingly difficult for particles to overcome the effect of gravity to report to the reject end. As the higher fraction of stratified material move towards product end the separation density increases hence reducing the quality of clean coal.

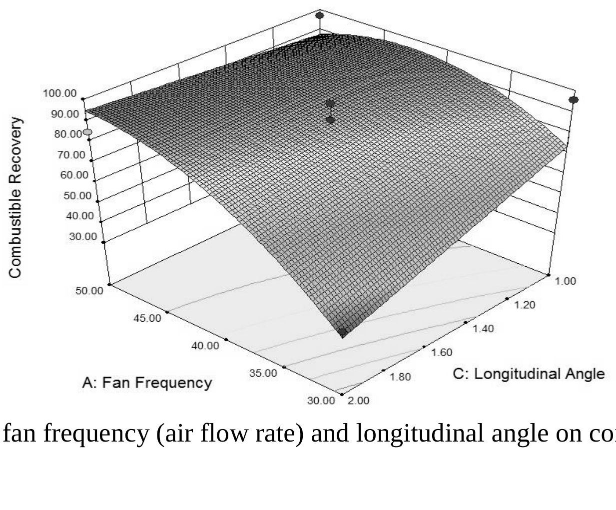


Figure 7. Effect of fan frequency (air flow rate) and longitudinal angle on combustible recovery.

The higher table frequency decreased the product yield and ash thus indicating larger movement of material towards reject end. From tests using higher table frequency values, it was observed that the entire particle bed moved towards reject end. This behavior may be due to the fact that, at higher table frequency, the particle residence time is very low and, as a result, the particles begin to discharge prior to the formation of the bed.

The results of the Box-Benkhen design tests are plotted in Figure 8. These results show the achievement of clean coal containing approximately 7.7 % ash with about 60 % yield from a feed coal having 26% ash with a combustible recovery of 65 %. The ash rejection is about 80 %. Many of the test runs achieved recovery values close to the optimum performance provided by washability analysis which is reflective of the high level of cleanability of the PRB coal and the relative effectiveness of the separation achieved by the air table.

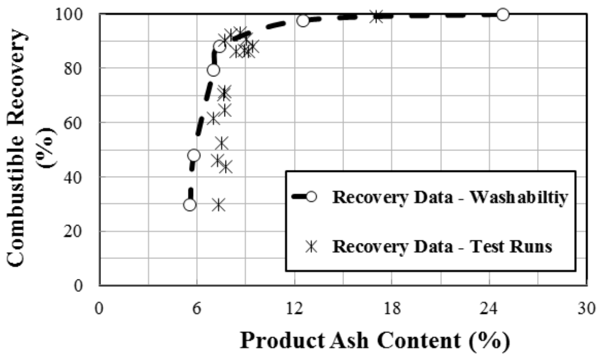


Figure 8. Separation performance achieved from the treatment of 6 x 1 mm sub-bituminous coal using a laboratory air table over a range of operating conditions.

Further tests were conducted to verify the optimum test conditions identified using the empirical relationships generated from data collected from the parametric experimental program. The optimal results are provided in Table 2 and a photograph of the products is provided in Figure 9.

Table 2. Optimum separation performance achieved when treating 6 x 1 mm coal using the air table.

Feed Ash (%)	Product Ash (%)	Mass Yield (%)	Combustible Recovery (%)	Ash Rejection (%)
26.62	7.04	66.60	84.37	82.4

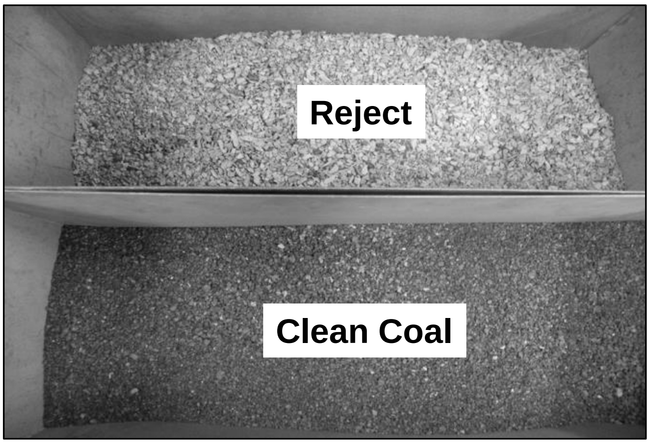


Figure 9. Photograph of the clean coal and reject generated from cleaning the 6 x 1 mm sub-bituminous coal using an air table.

Partition curve data from float sink analysis of the optimized test run product and the reject samples reveal that it is possible to obtain low Ep values of 0.12 and 0.22 and separation densities between 1.58 gm/cm^3 and 1.88 gm/cm^3 as shown in Figure 10. Here, Test 1 and Test 2 correspond to the optimized test runs.

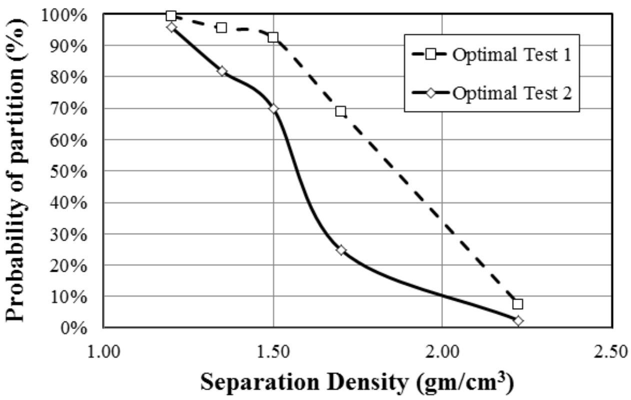


Figure 10. Partition curves generated from the optimum performance achieved from the treatment of the 6 x 1 mm coal using an air table.

4. CONCLUSIONS

The on-site pilot scale and the laboratory test program successfully evaluated an effective dry processing method to clean low rank coal. The data from the sample analysis and optimized tests performed during the test program were examined and statistically significant empirical models were developed for product ash and yield in terms of operating parameters. The pilot scale test data showed that the finer size fraction of minus 6 mm has a greater tendency to report to the product stream and hence would require a different process to clean. As such, two separate units are required to effectively treat material coarser than 6 mm and finer than 6 mm. The projected optimal performance is provided in Table 3.

Table 3. Projected performance for an air table separator treating a sub-bituminous coal.

Performance Parameters	Particle Size Fraction	
	75 x 6 mm	Minus 6 mm
Feed Weight (%)	78.99	21.01
Feed Ash (%)	18.15	26.62
Mass Yield (%)	82.1	66.6
Product Ash (%)	6.19	7.04
Overall Yield (%)	78.9	
Overall Product Ash (%)	6.34	
Overall Combustible Recovery (%)	92.2	

The optimal test results show that a sharp separation can be achieved for the 75 x 1 mm PRB coal with minimal coal loss. Ash analysis of optimized test data shows that it is possible to obtain a composite clean coal product having approximately 7 % ash with about 78.9 % yield from a feed coal having 19.93% ash with an overall combustible recovery of 92.2 %. The major conclusions of the test program can be listed as follows:

i. Out-of-seam or parting material can be effectively removed from the PRB coal using dry, fluidized bed table separators to produce a marketable product.
ii. The high inherent moisture values of PRB coal enhances the effectiveness of dry separators.
iii. Maintaining sufficient air flow rate through the bed is critical to ensure maximum combustible recovery.
iv. Ash rejection is controllable by table slope and table frequency.
v. Product ash values of around 7% were achieved when operating with optimum parameter value settings unique to each size fraction.

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