FINAL TECHNICAL REPORT
October 1, 2007, through April 30, 2009

Project Title: **ON-SITE EVALUATION OF THE STACK SIZER IN CONJUNCTION WITH THE FALCON CONCENTRATOR**

ICCI Project Number: 07-1/9.1B-2
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ABSTRACT

Stack Sizer is a relatively recent development from Derrick Corporation. It has fine urethane screen surfaces in the range of 100 to 75 microns. The main goal of this project was to evaluate the fine coal screening performance achieved by an industrial scale Stack Sizer and demonstrate a new fine coal cleaning circuit consisting of a Stack Sizer and a Falcon Concentrator for cleaning high sulfur Illinois coal.

A single deck Stack Sizer in conjunction with a C400 Falcon Concentrator having a feed handling capacity up to 5 tph were used in this study. The complete experimental program was conducted at the Creek Paum Mine of Knight Hawk Coal Company. The Stack Sizer was successfully evaluated using both 75-micron and 100-micron panels. High efficiency size separation, described by an *imperfection* value of 0.21 and ultrafine bypass of 4.72% at a d_{50c} of 76.7 microns, was achieved using a 75-micron panel. Corresponding efficiency measures for the 100-micron panel were 0.27, 4.91% and 98.2 microns, respectively. Both urethane mesh panels had rectangular openings. The complete fine coal cleaning circuit produced a clean coal product with minimum ash content of 7.65% from a 30% ash feed stream. This was the result of high efficiency size separation achieved at the Stack Sizer and high efficiency ash rejection achieved at the Falcon Concentrator for cleaning nominally +200-mesh coal. A reasonably low 1.74 specific gravity of separation was achieved by the Falcon Concentrator along with a probable error (Ep) value of 0.13 for cleaning nominally 16 X 200-mesh coal. However, 9.21% of the coarse clean coal was rejected to the tailings stream.

An economic analysis was conducted to compare the cost of fine coal cleaning with a traditional circuit consisting of classifying cyclones, spirals and flotation cells and the proposed circuit consisting of Stack Sizers and Falcon Concentrators. For a hypothetical fine coal cleaning circuit treating 100 tph of raw coal, the estimated total cost per ton of feed coal for the traditional fine coal cleaning circuit and the proposed new circuit are $4.93 and $5.89, respectively. The corresponding cost figures per ton of clean coal are $8.08 and $9.65, respectively. The PI believes that the significant reduction in sulfur penalty due to better pyrite rejection achievable with the proposed circuit may very well offset the higher cost of cleaning when the feed is high sulfur coal.

EXECUTIVE SUMMARY

Froth flotation processes, especially flotation columns, are well known for their excellent ability to reject ash-forming minerals from fine coal. However, ash-forming minerals are not the only impurities of concern in Illinois coal. Sulfur bearing minerals like coal pyrites are also highly undesirable in the clean coal product. However, coal pyrite particles are known to be weakly hydrophobic; in addition, their hydrophobicity is significantly enhanced with the addition of fuel oil collector in the froth flotation process. According to Olson and Aplan (1984 and 1987), the addition of fuel oil enhances the floatability of coal pyrite particles in the size range of 65 X 200-mesh by more than thirty times; whereas the improvement in floatability for clean coal particles in the same size range is only three times. Since fuel oil addition (about 1 lb/ton) is common practice in the flotation process, it is not uncommon to note sulfur content of flotation concentrate being higher than that of feed coal.

Because of the significant difference in specific gravity (4.8 for pyrite versus 1.3 for clean coal), enhanced gravity based separators have been shown to provide excellent sulfur rejection performance. Successful studies (Luttrell et al., 1995; Riley et al., 1995; Honaker et al., 1995; Venkatraman et al., 1995; McAllister, 1998; Mohanty and Honaker, 1999) have established the effective ash and pyritic sulfur cleaning performance achieved by enhanced gravity separators particularly in the particle size fraction of 600 to 45 microns. In fact, some of these studies have reported superior ash and sulfur cleaning performance of enhanced gravity separators in comparison to flotation columns in this particle size range. The Falcon Concentrator was one such enhanced gravity separator that was developed with ICCI funding from a lab-scale batch unit to a continuous unit operating at 100 tph by Honaker (1995) and Honaker et al. (1995). A low cost, high capacity enhanced gravity separator like the Falcon Concentrator could be used very effectively to reject coal pyrites while achieving high Btu recovery, thus lowering the sulfur dioxide (SO_2) emission potential of high sulfur Illinois coal. However, the Falcon Concentrator is known to perform effectively only up to a bottom particle size limit of 325-mesh and its performance deteriorates sharply below this particle size. In fact, Falcon Concentrator performance for the 200- X 325-mesh size fraction is significantly inferior to that of coarser size fractions. Thus, a precise particle size separation between 200- to 325-mesh is an essential condition for high performance cleaning achievable with the Falcon Concentrator. Since particle size classification achieved by cyclones, the most common fine coal classifier, is not precise due to as much as 30% misplacement of ultrafine particles in the underflow stream, the Falcon Concentrator has yet to find its place in coal preparation plants in Illinois.

Mohanty et al. (2008) developed and demonstrated a fine coal cleaning circuit using the Falcon Concentrator and the Pansep Screen for cleaning high sulfur coal. However, Pansep Screen, which is a South African technology, has yet to be commercialized in the US coal industry. Meanwhile, Derrick Corporation, a well known screen manufacturer, has commercialized a new fine coal screening technology, known as Stack Sizer™. Therefore, the main goal of this project was to evaluate the fine coal screening

performance achieved by an industrial scale Stack Sizer and demonstrate a new fine coal cleaning circuit consisting of a Stack Sizer and a Falcon Concentrator.

A single deck Stack Sizer was used in this study to match with the feed handling capacity of a C400 Falcon Concentrator. The complete experimental program was conducted at the Creek Paum Mine of Knight Hawk Coal Company. The Stack Sizer was successfully evaluated using both 75-micron and 100-micron polyurethane mesh panels. High efficiency size separation, described by an *imperfection* value of 0.21 and ultrafine bypass of 4.72% at a d_{50c} of 76.7 microns, was achieved using 75-micron panel. The corresponding efficiency measures for the 100-micron panel were 0.27, 4.91% and 98.2 microns, respectively. Both urethane mesh panels had rectangular openings. Sieve bends, which are commonly used in coal preparation plants for fine coal screening, were found to produce much inferior size separation performance, which can be summarized by an *imperfection* value of 0.55, d_{50c} of 116.5 microns and ultrafine bypass of 35.2%.

A new fine coal cleaning circuit consisting of a Stack Sizer and a Falcon Concentrator produced a clean coal product having a minimum ash content of 7.65% by treating a feed with ash content of nearly 30%. This was a result of high efficiency size separation achieved at the Stack Sizer and high efficiency ash rejection achieved at the Falcon Concentrator for cleaning nominally +200-mesh coal. A reasonably low specific gravity of separation of 1.74 was achieved by the Falcon Concentrator along with a probable error (Ep) value of 0.13 for cleaning nominally 16- X 200-mesh coal. However, 9.21% of the coarse clean coal was rejected to the tailings stream. This may indicate the particle size treated is too wide for effective coal cleaning by the Falcon Concentrator.

An economic analysis was conducted to compare the cost of fine coal cleaning obtained by the traditional fine coal cleaning circuit consisting of classifying cyclones, spirals and flotation cells and the proposed circuit consisting of Stack Sizers and Falcon Concentrators. Based on a hypothetical fine coal cleaning circuit treating 100 tph of raw coal, the estimated total cost per ton of feed coal for the traditional fine coal cleaning circuit and the proposed new circuit were $4.93 and $5.89, respectively. The corresponding cost figures per ton of clean coal are $8.08 and $9.65, respectively. The estimated payback periods for a traditional fine coal cleaning circuit and the proposed cleaning circuit are 17 and 22 months, respectively.

Although the estimated cost of fine coal recovery using the proposed circuit is $1.57 higher than the traditional circuit on a clean ton basis, it is believed that the significant reduction in sulfur penalty due to better pyrite rejection achievable by the proposed circuit may very well offset this higher cost of cleaning for high sulfur coal. A simple analysis indicates that if the proposed circuit can produce a clean coal product having sulfur content 0.85% lower than that of the clean coal product obtained from the traditional circuit, this cost differential can be completely eliminated. The above analysis is based on a typical sulfur penalty of 10 cents per ton of coal for each 0.1 lb SO_2/MBtu over the contract specification and an average clean coal heating value of 11000 Btu/lb.

OBJECTIVES

The overall goal of the proposed study was to evaluate the ultrafine size separation performance achievable from a Stack Sizer at a plant site and demonstrate the performance of a novel fine coal cleaning circuit consisting of a Stack Sizer and a Falcon Concentrator. Toward this goal, the specific project objectives were:

1. To conduct an experimental study at a plant site to evaluate the performance of the Stack Sizer for fine and ultrafine size separations.
2. To demonstrate the performance achievable from a new fine coal cleaning circuit consisting of Stack Sizer and Falcon Concentrator.
3. To conduct an economic analysis to compare the cost of coal cleaning for the new circuit and a traditional fine coal cleaning circuit.

INTRODUCTION AND BACKGROUND

The physical separation processes utilized in coal preparation plants to obtain the desired Btu recovery and pyrite rejection are effective only in a specified particle size range. The process efficiency deteriorates drastically beyond an optimum particle size range. For example, the conventional flotation process achieves an effective separation in the 60- X 325-mesh particle size range. The presence of finer clays (–325-mesh) affects the separation process significantly due to the hydraulic entrainment problem. Many preparation plant operators complain that the performance from their flotation banks suffers due to the presence of undesirable ultrafine clay particles in their flotation feed even after undergoing a desliming (classification) step.

Froth flotation processes, especially column flotation, are known to provide excellent ash rejection performance while cleaning fine coal. However, ash forming minerals are not the only impurity of concern in Illinois coal. Sulfur bearing minerals like coal pyrites are also highly undesirable in the clean coal product. However, coal pyrite particles are known to be weakly hydrophobic; in addition, their hydrophobicity is significantly enhanced with the addition of fuel oil collector in the froth flotation process. According to Olson and Aplan (1984 and 1987), addition of fuel oil enhances the floatability of coal pyrite particles in the 65- X 200-mesh size range by more than thirty times; whereas the improvement in floatability for clean coal particles in the same size range is only three times. Therefore, it is not uncommon to note sulfur content of flotation concentrate being higher than that of feed coal. Because of the significant difference in specific gravity (4.8 for pyrite versus 1.3 for clean coal), enhanced gravity based separators have been shown to provide significantly better sulfur rejection performance than flotation columns. The Falcon Concentrator was one such enhanced gravity separator that was developed with ICCI funding from a lab-scale batch unit to a continuous unit operating at 100 tph by Honaker (1995) and Honaker et al. (1995). A low cost and high capacity enhanced gravity separator like the Falcon Concentrator can be used very effectively to reject coal pyrites while achieving a high Btu recovery, thus lowering the sulfur dioxide (SO_2) emission potential of high sulfur Illinois coal. However, the Falcon Concentrator is known to perform effectively only up to a bottom particle size limit of 325-mesh and below that, its performance deteriorates sharply. In fact, the Falcon Concentrator performance for the 200- X 325-mesh size fraction is significantly inferior to that of coarser size fractions. Thus, a precise particle size separation between 200- to 325-mesh is an essential condition for high performance cleaning achievable by the Falcon Concentrator. Since particle size classification achieved by cyclones, the most common fine coal classifier, is not precise due to as much as 30% misplacement of ultrafine particles in the cyclone underflow stream, the Falcon Concentrator has yet to find its place in coal preparation plants in Illinois.

The Stack Sizer is a relatively recent development from Derrick Corporation. It has multiple fine urethane screen surfaces in the range of 100 to 75 microns. As shown in Figure 1, Stack Sizer consists of multiple (up to five) screen decks operating in parallel to each other. The linear motion provided to the screen decks by Derrick Corporation's Super G[TM] vibrating motors, together with an angle of inclination between 15 and 25 degrees, produces excellent efficiency with high oversize capacity (Derrick Corporation, 2009). The entrapped fines in the coarse overflow are released by repulping the initial overflow material with wash water in a trough between the upper and lower section of the screen deck. This repulping process allows the fines to find their way through the screen openings thereby minimizing ultrafine bypass to the overflow product.

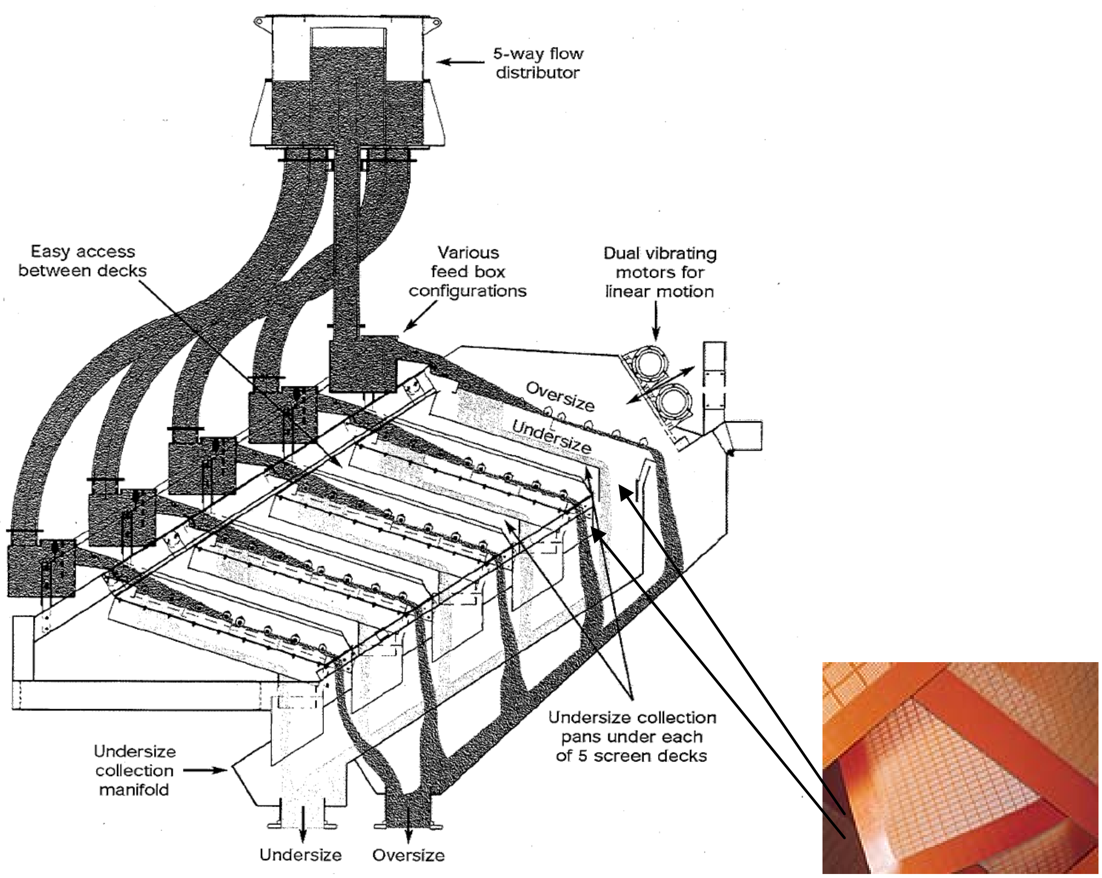


Figure 1: Schematic of full-scale Stack Sizer with five parallel screen decks (inlet). (Derrick Corporation, 2009)

This project entailed an evaluation of the screening efficiency of a Stack Sizer at a mine site using both 100-micron and 75-micron mesh panels. After indentifying the optimum operating conditions, the Stack Sizer was operated in conjunction with a Falcon Concentrator to clean nominally –1-mm coal. The Stack Sizer overflow was fed to the Falcon Concentrator to produce the fine clean coal product.

EXPERIMENTAL PROCEDURES

A single deck Stack Sizer having a throughput capacity of 5 tph was utilized in this test program. The first phase of the experimental program involved a thorough evaluation of the size separation efficiency achievable from a Stack Sizer at a coal preparation plant site as illustrated in Figure 2. As shown, a slip stream from the feed stream of the raw coal classifying cyclones operating at the host plant site was screened by the Stack Sizer using both 75-micron and 100-micron mesh panels. Several series of exploratory tests were conducted to get a better understanding of the Stack Sizer operating principles by varying the process parameters like vibration frequency over the range of 30 to 60 Hz, screen inclination from 17.5 to 22.5 degrees, and spray water rate from 152 to 227 liters per min (L/Min). Since screen inclination at the medium level provided better size separation performance than that at the other two levels, the optimization test program utilized the medium level of screen inclination for all tests. Factors varied during the optimization test program, which consisted of 18 tests, included feed flow rate (from 200 L/Min to 400 L/Min), deck vibration frequency (from 40 to 60 Hz) and wash water rate (from 114 L/Min to 189 L/Min).

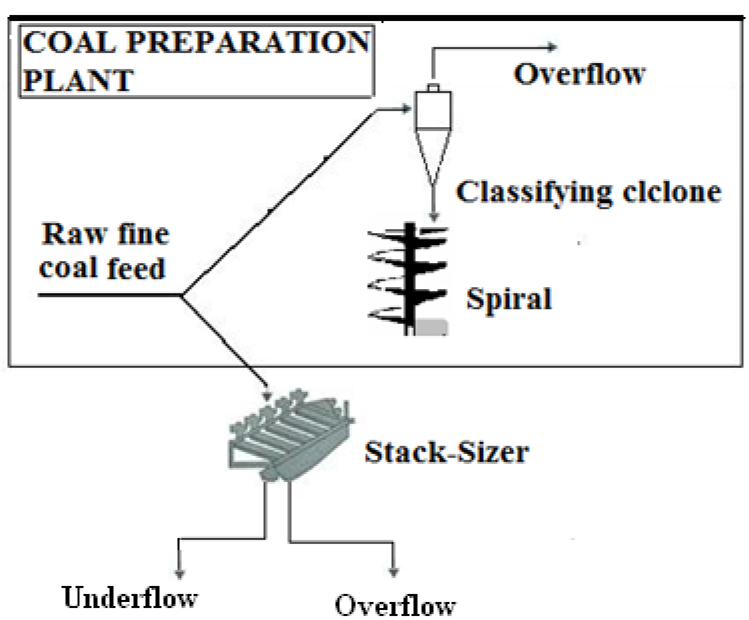


Figure 2: Experimental set-up utilized for evaluating size separation performance of a single deck Stack Sizer using 75- and 100-micron mesh panels.

The Falcon Concentrator, which has been thoroughly investigated in the past for its suitability for high sulfur coal cleaning, was evaluated in the second phase of the experimental program as a part of a new fine coal cleaning circuit in which Stack Sizer overflow was fed to the Falcon Concentrator to produce fine clean coal concentrate. The flow sheet (see Figure 3) utilized a Model C400 Falcon Concentrator with 5 tph capacity.

Size analyses of +200-mesh and –200-mesh test samples were conducted using standard laboratory wet sieving method and Mircotrac^{TM} method, respectively. Ash and sulfur analyses of test samples were conducted using ASTM prescribed procedures.

RESULTS AND DISCUSSION

Task 1: Installation of the Stack Sizer at a Plant Site

A single deck Stack Sizer and a C400 Falcon Concentrator were mounted on a steel trailer and positioned on a concrete platform next to the preparation plant at Knight Hawk Coal Company's Creek Paum Mine. A 480-volt power supply for both Stack Sizer and Falcon Concentrator motors was obtained from the host plant switch box. A 2-inch diameter slip stream was taken from the plant's raw coal classifying cyclone feed stream to feed the Stack Sizer. A 24-inch diameter gyratory screen was installed to prevent oversize (+16-mesh) material from reporting to the Falcon Concentrator. A picture of the plant site installation is shown in Figure 4.

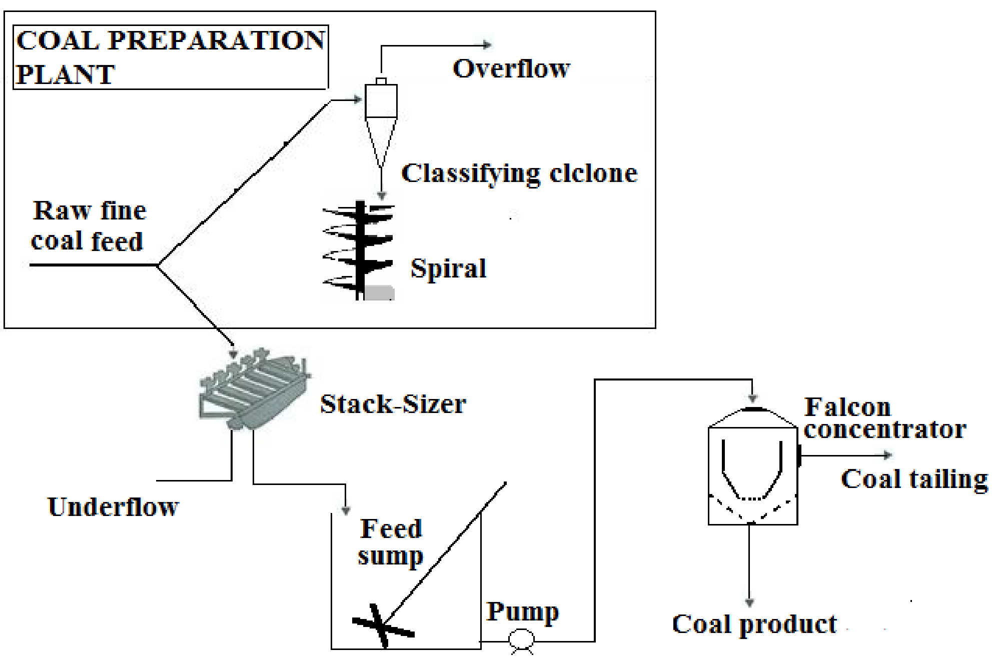


Figure 3: Experimental set-up utilized to evaluate a new fine coal cleaning circuit consisting of a Falcon Concentrator and a Stack Sizer.

Figure 4: Single deck Stack Sizer and C400 Falcon Concentrator at Creek Paum Mine.

Task 2: Stack Sizer Experimental Program

The Creek Paum Mine utilizes a banana screen to classify plant feed coal at about 2-mm. The +2-mm coal is cleaned using dense medium cyclones and the –2-mm is reclassified at 150 microns. Due to gradual deterioration of mesh screen panels and their consequent replacement, the size-by-size ash and weight distribution in the Stack Sizer feed altered quite a bit during the test program. An example of this feed alteration is illustrated in Table 1, which indicates that the d_{80} size of Stack Sizer feed samples collected in different months during the test program varied from nearly 400 microns to 1300 microns. The overall ash content varied from 27.2% to 38.8%; in fact, a feed sample collected outside the project time period had an ash content of 48.8% and a size distribution closer to that of the Feed 1 sample shown in Table 1.

Task 2.1: Exploratory Test Program

During the initial week of the test program, Mr. Paul Brodzik, a technical specialist from Derrick Corporation, was on site to train project staff on Stack Sizer operations. Several series of exploratory tests were conducted using 100-micron mesh panels to get familiar with the equipment and assess Stack Sizer process parameter values as recommended by Mr. Brodzik. As illustrated in Figure 5(a), separation size (d_{50c}) increased from 60 microns at a vibration frequency of 30 Hz to nearly 95 microns at 45 Hz, beyond which it remained nearly constant up to the maximum vibration frequency of 60 Hz. An optimum *imperfection* value of nearly 0.26 was obtained at 50 Hz. Ultrafine bypass to the Stack

Sizer overflow increased up to nearly 20% with an increase of vibration frequency to 60 Hz. For the above series of tests, the feed flow rate, spray water rate, and screen inclination were maintained constant at 400 L/Min, 189 L/Min and 20^o, respectively.

Table 1: Variation in the size-by-size weight distribution of the Stack Sizer feed coal slurry collected at different times during the experimental program.

Feed 1 Size Analysis				
Sieve No	Size (micron)	Wt%	Cum. Passing Wt %	Ash %
+6	3360	0.27	99.73	17.10
-6+10	2000	5.21	94.52	14.89
-10+16	1000	23.06	71.46	15.65
-16+60	250	24.16	47.30	17.77
-60+100	150	5.61	41.69	19.38
-100+200	75	7.67	34.03	20.85
-200+325	45	4.85	29.17	23.08
-325+500	25	5.02	24.16	27.93
-500	5	24.16	0	54.81
Total		100.00		27.17
Feed 5 Size Analysis				
Sieve No	Size (micron)	Wt%	Cum. Passing Wt %	Ash %
+6	3360	0.00	100.00	
-6+10	2000	0.00	100.00	
-10+16	1000	3.90	96.10	27.54
-16+60	250	33.41	62.69	25.75
-60+100	150	8.25	54.44	23.81
-100+200	75	9.94	44.50	30.80
-200+325	45	5.90	38.60	35.95
-325+500	25	6.11	32.49	44.40
-500	5	32.49	0.00	59.24
		100.00		38.78

The effect of screen inclination and wash water rate on the three process responses were studied in two subsequent test series. The lowest *imperfection* value of 0.21 and a d_{50} of about 74 microns were obtained at the medium deck inclination level, as shown in Figure 5(b). The ultrafine bypass was also near its lowest level of nearly 6% at this deck inclination. Therefore, the medium deck inclination level was used for all tests during the optimization test program. A wash water level of 60 gpm (228 L/Min) appeared to be too high based on visual observations during exploratory tests. As shown in Figure 5(c), the highest wash water level resulted in higher *imperfection* (i.e., lower efficiency) and higher ultrafine bypass values. Therefore, wash water rates in the lower range were utilized during the optimization test program.

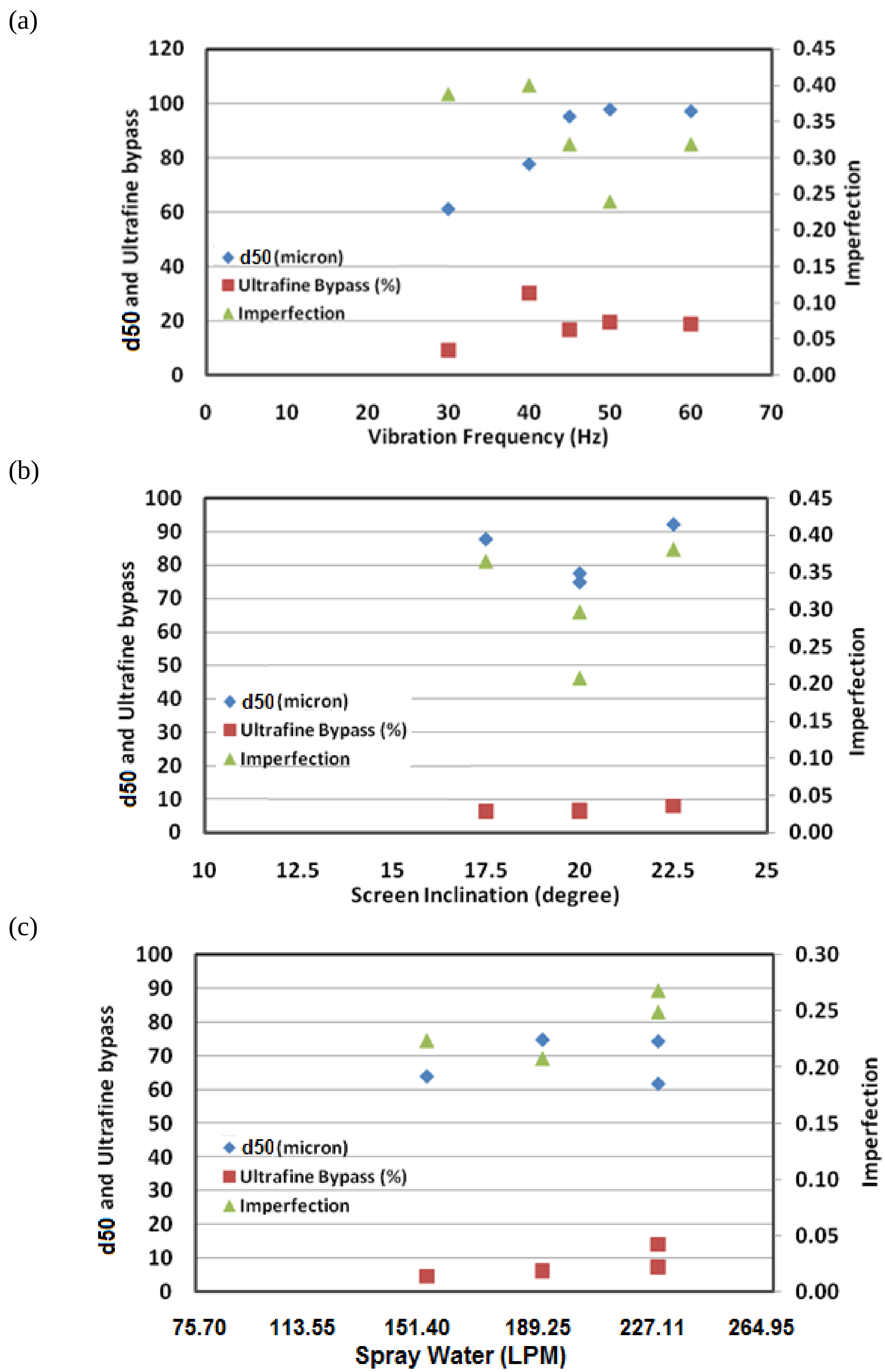


Figure 5: Stack Sizer exploratory test program results using a 100-micron mesh panel.

Task 2.2: Optimization Test Program

An optimization test program following a Central Composite Design was conducted to further investigate parametric main effects and interaction effects on various process responses. Based on findings obtained from Task 2.1, the screen deck inclination was maintained constant at the medium level. The wash water rate was varied over a lower range of 114 to 189 L/Min, whereas the feed rate was varied over a range of 200 to 400 L/Min. Exact operating conditions for each test and resulting size separation performances are listed in Table 2. As indicated, d_{50} values varied over a range of 77 to 108 microns during the experimental program. Although the d_{50} is commonly finer than mesh openings in screening processes, this phenomenon may not hold true for mesh panels with rectangular openings. In such cases, particles slightly coarser than the average mesh opening size may pass through rectangular openings and report to the screen underflow, especially in high solid loading conditions. This may be why the d_{50c} values obtained from two tests (Tests 9 and 16) are slightly coarser than the average rectangular mesh opening size of 100 microns. Overall, ultrafine bypass and screening *imperfection* varied from 4.9 to 14.3% and 0.27 to 0.35, respectively.

The relative effect of each process parameter for all three process responses are illustrated by statistical perturbation plots in Figure 6. As shown in Figure 6(a), the decreasing order of importance for all three process parameters in affecting d_{50c} is vibration frequency, feed flow rate and wash water rate. Increasing vibration frequency results in a coarser d_{50c} by increasing stratification, which allows more undersize particles to contact and pass through screen openings. High feed flow rate lowers the residence time of coal slurry on the screen surface and thus, may not allow sufficient time for all undersize particles to pass through screen openings. This phenomenon is believed to result in finer d_{50c} with increasing feed flow rate. Increasing wash water rate at troughs helps improve repulping action at the upper screen section overflow and releases entrapped undersize particles, which pass through screen openings in the bottom screen section. However, wash water rate had the least effect on separation size (d_{50c}).

Higher vibration frequency provided better screening efficiency, or in other words, resulted in a lower *imperfection* value, as shown in Figure 6(b). Higher *imperfection* values were observed with increasing flow rate apparently due to insufficient residence time. The slight increase in *imperfection* value with an increasing wash water rate may be due to increased amounts of misplaced undersize particles in the higher water content of the screen overflow. As Figure 6(c) indicates, vibration frequency and wash water rate had little effect on ultrafine bypass to the screen overflow. Feed flow rate at the medium inclination level provided lower ultrafine bypass than at low or high inclination levels.

Design Expert software was utilized to develop empirical models for all three responses. Model diagnostic tests allowed the successive elimination of a few outliers to develop suitable models for each response, as expressed in Equations 1 through 3, where A is feed flow rate (in L/Min), B is vibration frequency (in Hz), and C is wash water rate (in L/Min). Equation 1, a first order equation with F-ratio less than 0.0001 and R^2 equal to 0.92, was found to be suitable for d_{50c}. No interaction terms were found to be significant for the d_{50c} model. However, two interaction terms, i.e., feed flow rate-vibration frequency (AB) and feed flow rate-wash water rate (AC), were significant for the *imperfection* model. The same two interaction terms were also significant for the ultrafine bypass model, which was a second order equation.

$$d_{50} = 89.60 - 3.65A + 6.80B + 1.96C \qquad [1]$$

$$Imperfection = 0.31 + 0.022A - 0.022B + 0.012C - 0.014AB + 0.007AC \qquad [2]$$

$$Bypass = 7.57 - 0.60A + 0.90B + 0.10C - 1.54AB - 1.29AC + 2.43A^2 \qquad [3]$$

The three model equations were simulated to generate response surface contour plots, shown in Figure 7. Figure 7(a) clearly shows that low vibration frequency and high feed flow rate were conducive to finer separation size (d_{50}). The opposite trend was observed for *imperfection* response, as illustrated in Figure 7(b). Minimum ultrafine bypass was experienced with low feed rate and low vibration frequency, as shown in Figure 7(c).

Table 2: Stack Sizer optimization test program parameters and results.

Run	Feed Flow Rate (L/Min)	Vibration Frequency (Hz)	C:Wash Water Rate (L/Min)	d_{50c} (micron)	Imperfection	Ultrafine Bypass (%)
1	400	60	114	89.0	0.28	9.39
2	300	50	152	94.4	0.27	7.23
3	300	50	152	84.9	0.33	7.64
4	200	40	190	87.9	0.30	9.93
5	400	40	114	76.8	0.35	11.69
6	300	60	152	97.2	0.30	8.25
7	300	50	190	91.3	0.33	9.79
8	400	50	152	86.3	0.33	9.32
9	300	40	152	108.5	0.33	5.48
10	200	60	114	98.2	0.27	4.91
11	200	50	152	77.3	0.34	10.40
12	200	40	114	83.5	0.30	6.71
13	400	40	190	89.7	0.33	8.67
14	300	50	152	91.2	0.31	7.47
15	400	60	190	94.4	0.32	7.93
16	200	60	190	101.3	0.29	14.28
17	300	50	152	90.4	0.31	8.78
18	300	50	114	88.9	0.31	8.03

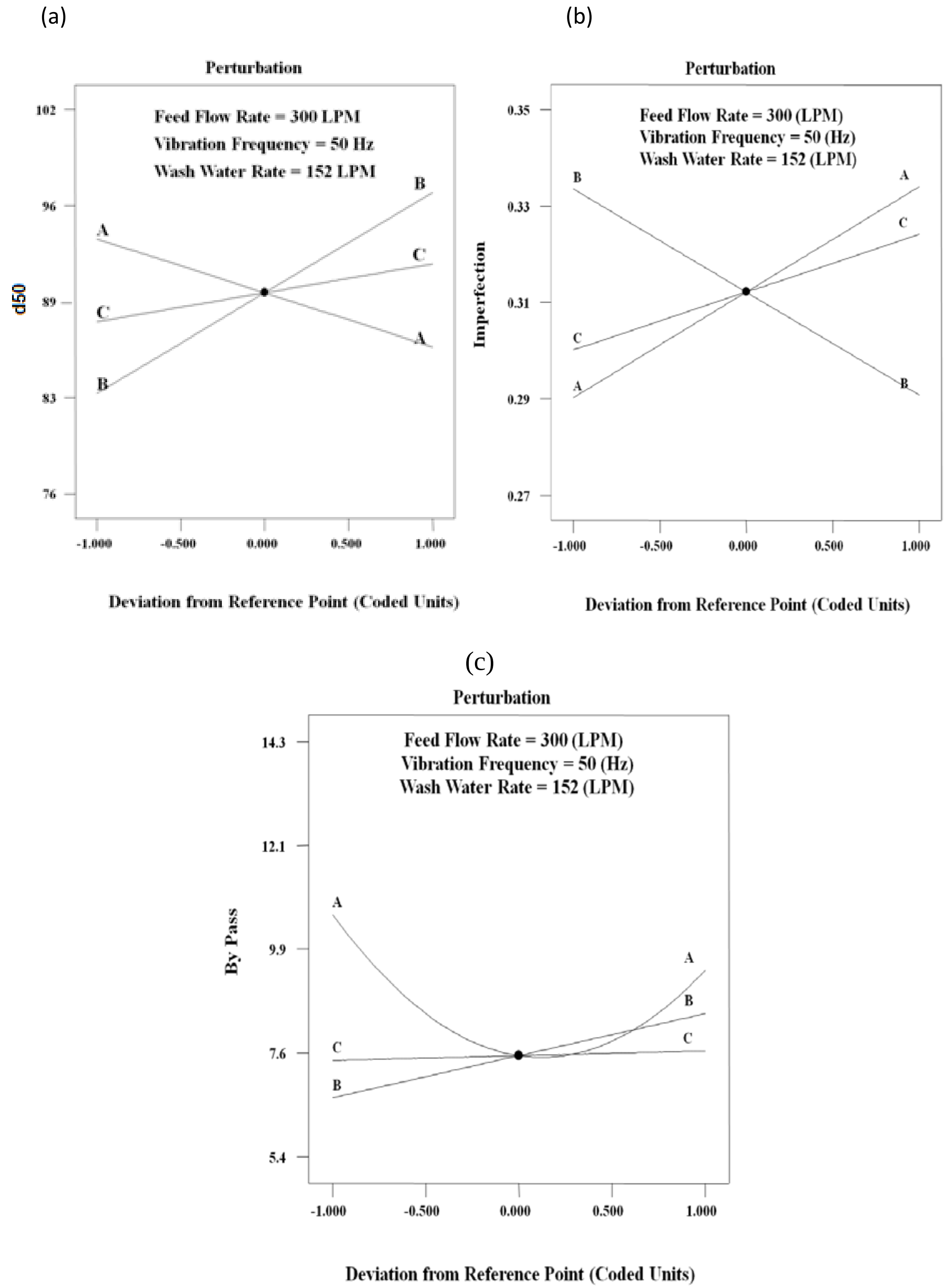


Figure 6: Statistical perturbation plots of key process responses. Process parameters are: A – Feed Flow Rate, B – Vibration Frequency, and C – Wash Water Rate.

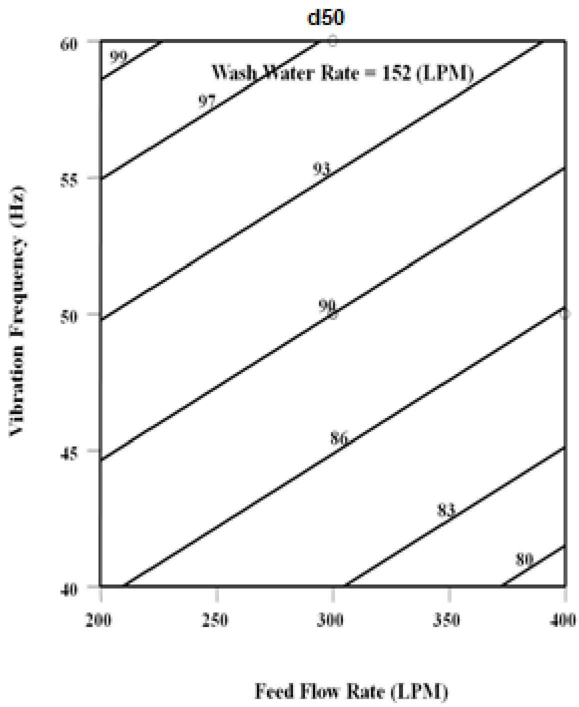
The majority of the size separation experiments in this study were conducted using the 100-micron mesh panel. Only a limited number of tests were done using the 75-micron mesh panel, since it got damaged quite early in the experimental program for some unknown reason. Size separation results obtained from a series of tests conducted with the 75-micron mesh panel are listed in Table 3. As shown, high efficiency size separation, represented by an *imperfection* value of 0.21 and ultrafine bypass below 5%, was achieved using the 75-micron mesh panel.

The impact of high efficiency size separation on ash removal from fine coal was also studied since finer size fractions in many US coals have a significantly higher concentration of ash forming mineral particles. Selected samples obtained from both 75-micron and 100-micron mesh panel tests were analyzed for ash content. As summarized in Table 4, high efficiency size separation at both 75 and 100 microns results respectively in rejection of 74.2% and 76.7% of ash forming minerals while recovering 66.4% and 38.2% of clean coal particles to the Stack Sizer overflow. The highest underflow ash content of 58.8% and 45.6% were obtained by using 75-micron and 100-micron mesh panels, respectively. The PI believes that a pure tailings stream having ash content close to 70% will be achievable using a 52-micron (270-mesh) panel, in which case froth flotation cleaning of the finest coal fraction in a preparation plant may not be necessary. This phenomenon will simplify the fine coal cleaning circuit of a modern day plant and also lower the fine coal cleaning cost significantly.

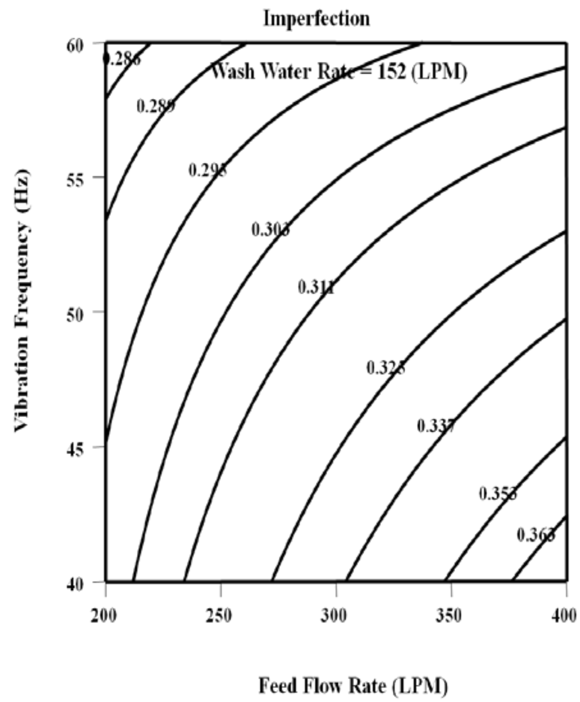
Table 3: Limited Stack Sizer results from 75-micron mesh panel tests.

Test ID	Vibration Frequency (Hz)	Spray water flow rate (gpm)	Screen Inclination (Degree)	Ultrafine Bypass (%)	*Imperfection*	d_{50} (micron)
1	60	50	20	8.42	0.30	83.0
2	45	50	20	6.62	0.30	77.6
3	45	50	20	6.19	0.21	74.9
4	30	50	20	4.72	0.21	76.7
5	45	60	20	14.08	0.25	61.7
6	45	35	20	13.69	0.22	63.9
7	45	60	20	7.43	0.27	74.5

(a)



(b)



(c)

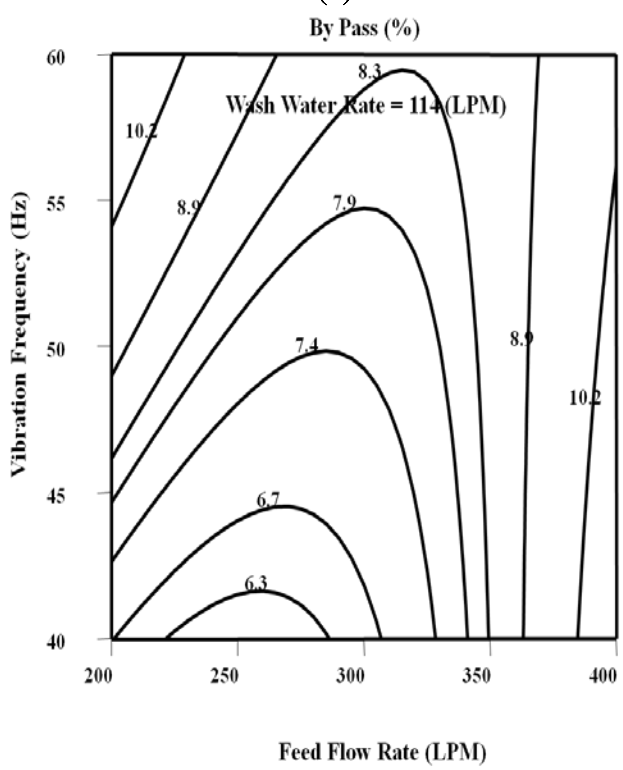


Figure 7: Response surface contours developed by simulating empirical models developed for three key process responses.

Table 4: Ash cleaning achievable by Stack Sizer screening of the raw coal cyclone feed.

Mesh Panel Used	Feed ash (%)	Overflow ash (%)	Underflow ash (%)	Yield to Overflow (%)	Combustible Recovery (%)	Ash Rejection (%)	Ash Separation Efficiency (%)
75	30.68	18.41	57.57	68.67	80.82	58.80	39.62
Micron	39.29	20.08	58.81	50.40	66.35	74.24	40.59
Screen	29.82	21.97	49.36	71.34	79.32	47.44	26.76
panel	25.17	17.79	52.35	78.65	86.40	44.41	30.82
	31.28	16.47	50.81	56.87	69.13	70.05	39.18
100	27.48	20.12	40.75	64.32	70.85	52.90	23.76
Micron	26.87	17.68	39.99	58.81	66.20	61.31	27.50
Screen	29.08	25.64	45.36	82.56	86.56	27.21	13.77
Panel	30	25.08	45.61	76.04	81.38	36.43	17.81
	35.74	25.37	40.82	32.88	38.19	76.66	14.85
	31.22	16.89	42.84	44.77	54.09	75.78	29.87

Task 3: Long-term Test and Stack Sizer Operation Demonstration

It is well known that plant feed characteristics are constantly fluctuating. Therefore, it was desired to do a long-term Stack Sizer test to investigate its sensitivity to continuously changing feed characteristics. The Stack Sizer was set at a specific operating condition and continuously operated for five hours without changing any controllable factors. As shown in Figure 8, the d_{50c} was maintained in the range of 75 to 100 microns. Efficiency parameters like *imperfection* varied over an acceptable range of 0.25 to 0.35, whereas ultrafine bypass was maintained within the range of 5 to 15%.

Preparation plant personnel from all three Knight Hawk Coal Company plants came at different times to witness the Stack Sizer operation first hand. A picture of the demonstration is shown in Figure 9.

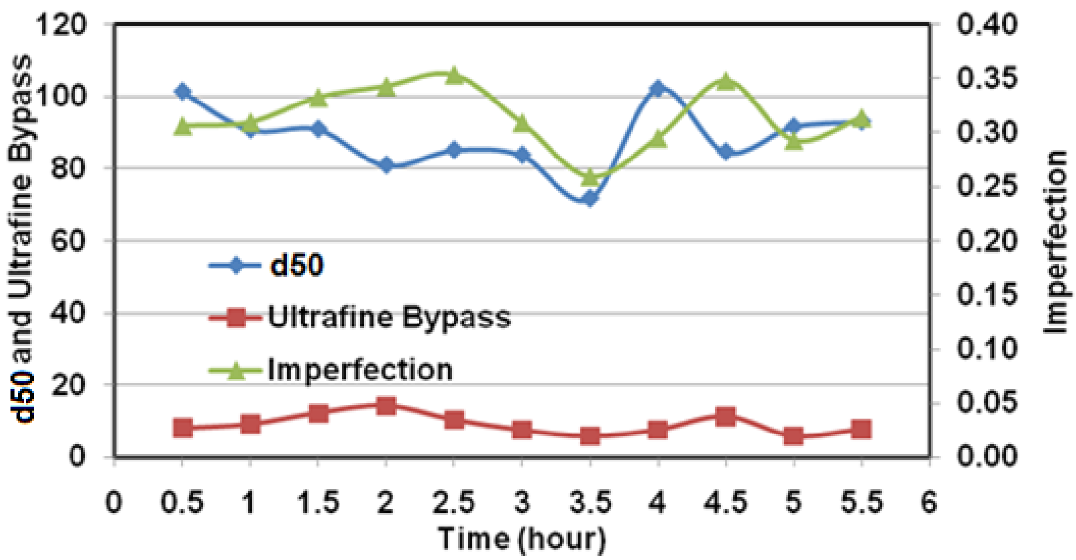


Figure 8: Stack Sizer sensitivity to fluctuating feed characteristics.

Figure 9: Stack Sizer demonstration at Knight Hawk Coal Company's Creek Paum Mine.

Task 4: Stack Sizer-Falcon Concentrator Circuit Integration and Testing

More than thirty tests were conducted in six different series using a C400 Falcon Concentrator to clean Stack Sizer overflow. A project engineer from Sepro Systems, the Falcon Concentrator vendor, was on-site during the initial week of the test work to ensure proper operation of the Falcon Concentrator. Since feed characteristics changed significantly from one series of tests to another, normalized process responses, such as combustible recovery and ash rejection, were used for comparison purposes. As illustrated in Figure 10, initial test series resulted in low combustible recovery and high ash rejection. Falcon Concentrator operating parameters, including bowl speed, tailings orifice pressure, and feed flow rate, were varied in subsequent test series to increase combustible recovery. Thus, Figure 10 shows results all along the grade-recovery domain. Higher combustible recovery and separation efficiency were achieved at lower bowl speeds that provide centrifugal fields in the range of 40 to 60 g-forces. The relationship between ash rejection and separation efficiency is shown in Figure 11.

Samples from ten tests that provided relatively high ash separation values were analyzed for total sulfur content to evaluate the sulfur rejection achieved by the Falcon Concentrator. As shown in Table 5, the highest ash separation efficiency was achieved with a combustible recovery of 83.8% and sulfur rejection of 48.5%. The sample with the highest ash rejection and sulfur rejection (both above 80%) was achieved at relatively low combustible recovery and mass yield values of 55.3% and 44.7%, respectively. Samples obtained from two tests that provided ash separation efficiency above 45% were subjected to float-sink analysis to generate density partition curves for the Falcon Concentrator. Both corrected and uncorrected partition curves are shown in Figure 12, which indicates some amount of low density clean coal particle bypass to the tailings stream and high density material bypass to the product stream. It is believed that the clean coal bypass is due to the rejection of relatively coarse clean coal particles, which may have same mass as mineral particles of much smaller size. The bypass of high density particles to the clean coal product is due to the recovery of relatively fine mineral particles, which may have similar mass as coarser clean coal particles. Table 6 lists effective specific gravity of separation values. A value of 1.74 means the Falcon Concentrator is able to produce a clean coal product having lower product ash content than that of coal spirals, which are known to have effective separation gravity above 1.8. However, the bypass of low density clean coal particles to the tailings stream may indicate that 1-mm X 75-micron particle size is too wide for effective cleaning in a single stage Falcon Concentrator.

A long-term test was conducted with the Falcon Concentrator to study its sensitivity to fluctuating feed characteristics. Figure 13 shows that combustible recovery remained nearly constant while ash rejection and separation efficiency varied considerably.

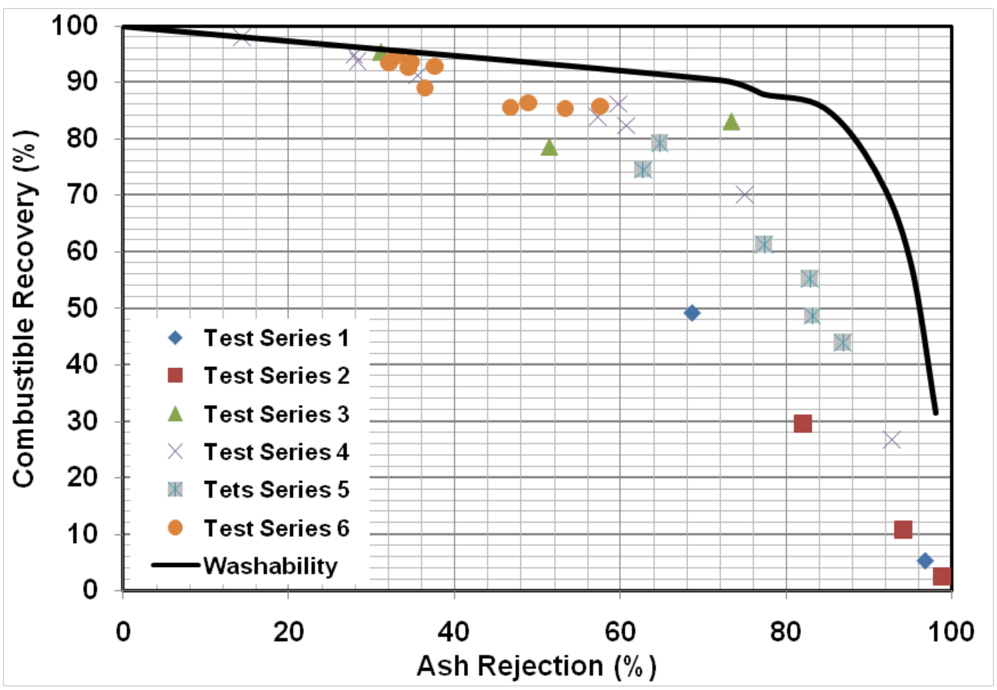


Figure 10: Combustible recovery versus ash rejection relationship.

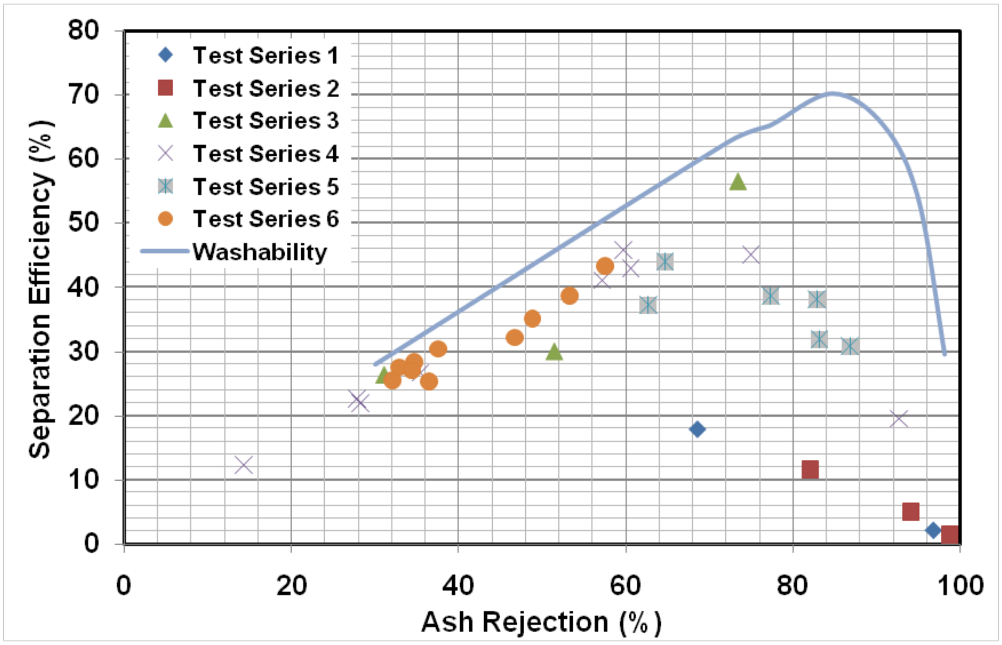


Figure 11: Separation efficiency versus ash rejection relationship.

Table 5: Ash and sulfur rejection performance of Stack Sizer-Falcon Concentrator circuit.

Ash			Sulfur		Yield (%)	Combustible Recovery (%)	Ash Rejection (%)	Sulfur Rejection (%)	Separation Efficiency (%)
Feed (%)	Product (%)	Tailing (%)	Feed (%)	Product (%)					
20.12	7.65	52.94	2.55	1.81	72.47	83.78	72.44	48.54	56.22
36.29	16.89	58.82	4.19	2.08	53.74	70.10	74.98	73.32	45.08
27.00	14.74	61.47	2.70	1.51	73.77	86.16	59.73	58.82	45.88
30.38	18.21	60.78	3.50	1.96	71.42	83.90	57.20	60.06	41.09
29.17	16.46	58.55	2.90	1.72	69.78	82.31	60.64	58.55	42.95
31.59	17.05	59.07	2.72	1.88	65.40	79.30	64.71	54.73	44.01
28.95	16.96	50.01	2.78	1.66	63.72	74.47	62.68	61.90	37.15
27.61	10.58	41.40	2.94	1.27	44.74	55.27	82.85	80.61	38.12
22.87	12.79	54.54	2.90	1.47	75.86	85.77	57.57	61.64	43.34
27.51	17.19	58.01	3.13	1.75	74.71	85.35	53.33	58.15	38.68

Table 6: Effective specific gravity of separation and probable error (Ep) achieved by Falcon Concentrator.

	Low Density bypass (%)	High Density bypass (%)	SG_{50C}	Ep
Test 4-3	9.21	0.98	1.74	0.13
Test 4-5	4.13	18.66	1.78	0.11

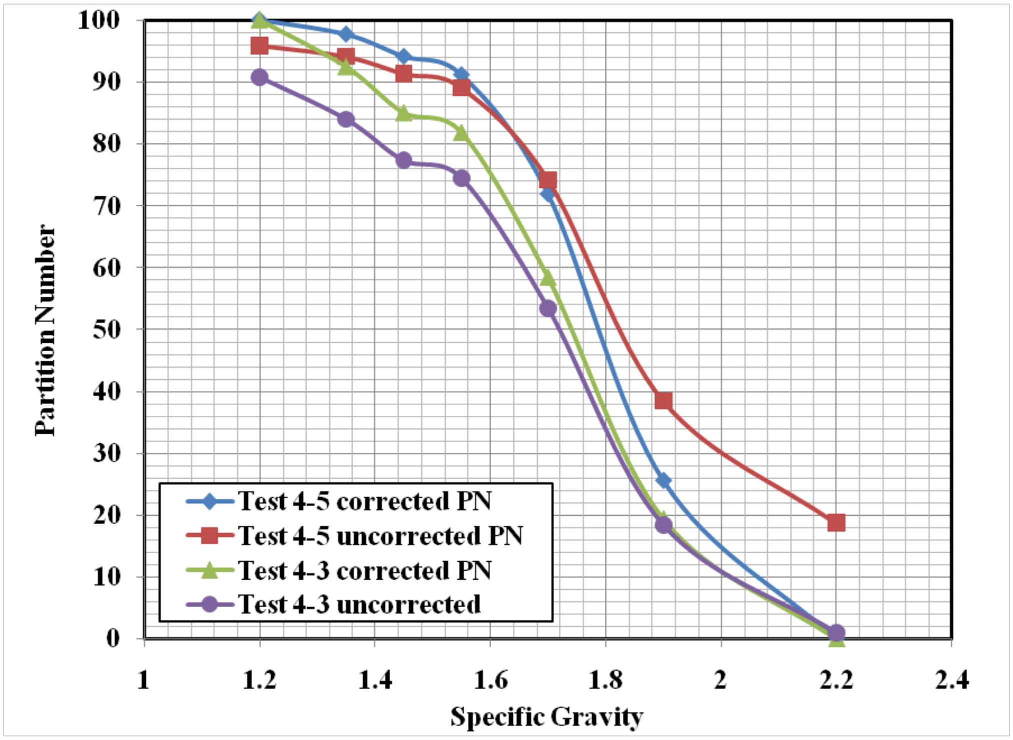


Figure 12: Partition curves for Falcon Concentrator at two different operating conditions.

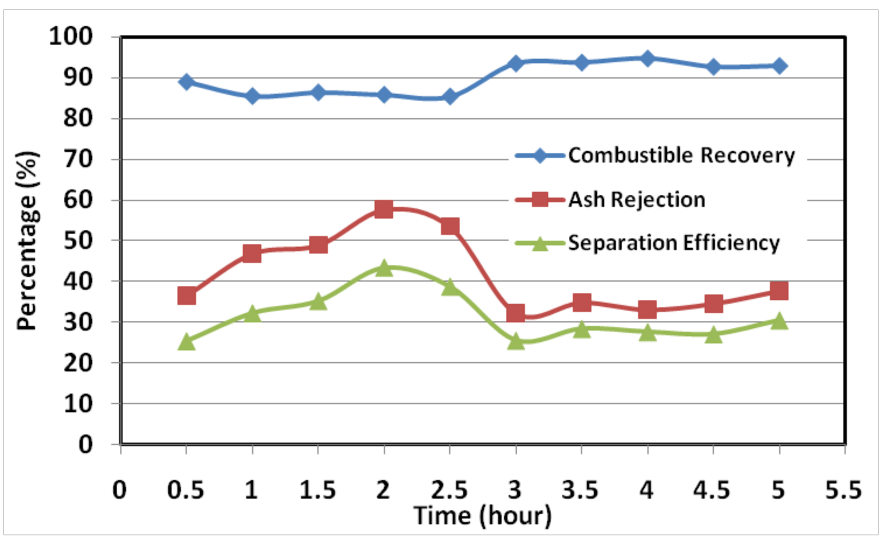


Figure 13: Long-term test data collected for Falcon Concentrator.

Task 5: Economic Analysis

In order to estimate the viability of the proposed fine coal cleaning circuit, an economic analysis was conducted to compare the cost of fine coal cleaning and dewatering using a traditional circuit versus the proposed flow sheet. A traditional fine coal cleaning and dewatering circuit may be represented by a combination of 15-inch and 6-inch diameter classifying cyclones, spirals, sieve bends, a flotation bank, disk filters and a thickener, as shown in Figure 14(a). The fine (1-mm X 0) raw coal feed flow rate was assumed to be 100 tph at a solid content of 15%. This circuit can be replaced by the proposed flow sheet consisting of Stack Sizers, Falcon Concentrators, disk filters and a thickener, as shown in Figure 14(b). Table 7 lists additional assumptions made for the traditional circuit to estimate both solids and water flow rates through individual process streams. These figures are based on commonly observed parameters in operating coal preparation plants. Table 8 lists similar assumptions made for the proposed circuit based on experimental data obtained during this investigation.

Capital and operating cost data for individual process unit operations except the Stack Sizer were obtained from a previous study (Patwardhan et al., 2003) in which the PI was a co-investigator. Those cost data were based on 2000 dollar values, which were updated to 2007 values using the Bureau of Labor’s price index multiplier of 1.54 (Bureau of Labor Statistics, 2009). Similar cost data were generated for the Stack Sizer based on direct consultation with the manufacturer (Brodzik, 2009). A factor of 2.5 has been used to convert capital cost data to total capital and installation costs based on consultation with a coal preparation plant design and construction company (Jain, 2006).

Table 7: Assumptions based on conventional wisdom for a traditional fine coal circuit.

Process Parameters	**Assumed Values**
Solid split at classifying cyclones	40:60 for overflow:underflow
Water split at classifying cyclones	80:20 for overflow:underflow
Ultrafine misplacement for cyclones	20%
Spiral solid yield	80%
Spiral water split	80:20 for product:tailings
Sieve bend overflow solid content	50%
Flotation yield	70%
Flotation product solid content	25%
Disk filter product moisture content	20%

Table 8: Assumptions based on findings of this project for the proposed fine coal circuit.

Process Parameters	**Assumed Values**
Solid split at Stack Sizer	80:20 (same level as conventional circuit)
Falcon Concentrator yield	75.86% (based on results obtained from Test 6.4)
Disk filter product moisture content	20% (same level as conventional circuit)

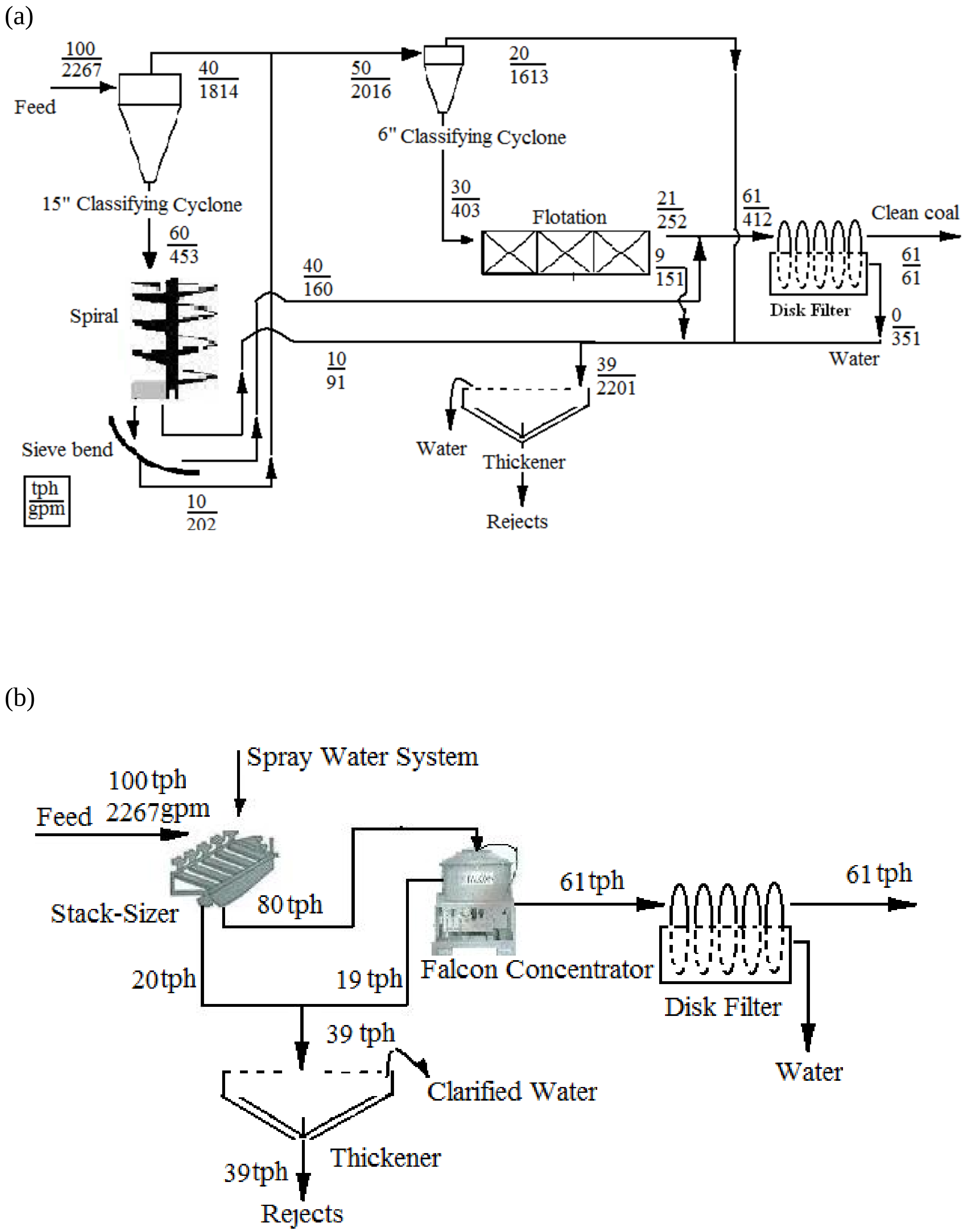


Figure 14: Comparative illustrations of (a) the traditional fine coal cleaning circuit, and (b) the proposed fine coal cleaning circuit for high sulfur coal.

As summarized in Table 9, a total investment of $8.42 million (in 2007 dollars) will be required to install a conventional fine coal cleaning and dewatering circuit. The estimated investment for the proposed fine coal circuit having the same feed and product throughput capacity is $11.25 million. However, it is well established that Falcon Concentrator product quality, especially pyritic sulfur content, is significantly better than that achievable with flotation cells (Honaker et al., 1995; Luttrell et al., 1995). Therefore, the proposed fine circuit is expected to produce a clean coal product with much lower sulfur content in comparison to that of the conventional fine coal circuit. This avoids sulfur penalty charges and may bring a higher price for the coal. Estimated payback periods are 17 and 22 months, respectively, for the conventional circuit and the proposed circuit, based on a coal price of $25/ton and 4000 working hours per year.

Table 10 summarizes fine coal cleaning and dewatering costs on a per ton basis. For the conventional circuit, costs per ton of feed coal and clean coal are $4.93 and $8.08, respectively. Corresponding costs for the proposed circuit are higher, i.e., $5.89 and $9.65, respectively. Although the estimated cost of fine coal recovery using the proposed circuit is $1.57 higher than the traditional circuit on a clean ton basis, it is believed that a significant reduction in sulfur penalty due to better pyrite rejection achievable with the proposed circuit may very well offset this higher cost of cleaning for high sulfur coal. A simple analysis indicates that if the proposed circuit can produce a clean coal product having sulfur content 0.67% lower than that of the clean coal product obtained from the traditional circuit, this cost differential can be completely eliminated. The above analysis is based on a typical sulfur penalty of 10 cents per ton of coal for each 0.1 lb SO_2/MBtu over the contract specification and an average clean coal heating value of 11000 Btu/lb.

Table 9: Estimation of comparative capital investments and payback periods.

Capital Investment Required at the Beginning		Capital+	Capital+	
		Installation Cost	Installation Cost	Investment Needed
Conventional Fine Coal Circuit	Tonage (tph)	(cent/ton)	(annual dollar)	
15" Cyclone	100	26.49	$ 105,960	
6" Cyclone	50	26.49	$ 52,980	
Spiral	60	20.21	$ 48,504	
Sieve Bend	50	22.45	$ 44,900	
Flotation	30	201.55	$ 241,860	
Thickener	39	74.04	$ 115,502	
Clean Coal Dewatering	61	360.94	$ 880,694	
Total Conventional Circuit			**$ 1,490,400**	**$ 8,420,339**
Proposed Fine Coal Circuit	Tonage (tph)	C&I Cost	Total Cost (dollar/hour)	
Stack-Sizer	100	103.99	415960.00	
Falcon Concentrator	80	181.22	579902.40	
Clean Coal Dewatering (Filter)	61	360.94	880693.60	
Thickener	39	74.04	115502.40	
Total New Circuit			**$ 1,992,058**	**$ 11,254,567**
Total Annual Revenue=	**$ 6,100,000**			
Pay back Period (Year)	**1.38**	for conventional circuit		
Pay back Period (Year)	**1.85**	for new circuit		

Table 10: Cost per ton estimates for conventional and proposed fine coal circuits.

Unit/Process	Operating Cost (cent/ton)	Capital Cost (cent/ton)	Capital and Installation Cost (cent/ton)	Total Cost (cent/ton)
Falcon Concentrator	18.05	72.49	181.22	199.27
Flotation	117.04	80.62	201.55	318.59
Classifying Cyclone	16.94	10.60	26.49	43.43
Spirals	10.40	8.09	20.21	30.61
Clean Coal Dewatering (Filter)	49.28	144.38	360.94	410.22
Thickener	43.43	29.61	74.04	117.46
Sieve Bend (Screen)	12.78	8.98	22.45	35.23
Stack-Sizer (Screen)	29.36	41.60	103.99	133.35
Conventional Circuit	Tonage (tph)	Total Cost (cent/ton)	Total Cost (dollar/hour)	
15" Cyclone	100	43.43	43.43	
6" Cyclone	50	43.43	21.71	
Spiral	60	30.61	18.36	
Sieve Bend	50	35.23	17.61	
Flotation	30	318.59	95.58	
Thickener	39	117.46	45.81	
Clean Coal Dewatering	61	410.22	250.23	
Total Conventional Circuit			492.74	
	Fine Coal Cleaning and Dewatering Cost/ton of feed coal=		**$ 4.93**	
	Fine Coal Cleaning and Dewatering Cost/ton of clean coal=		**$ 8.08**	
New Circuit	Tonage (tph)	Total Cost (cent/ton)	Total Cost (dollar/hour)	
Stack-Sizer	100	133.35	133.35	
Falcon Concentrator	80	199.27	159.41	
Clean Coal Dewatering (Filter)	61	410.22	250.23	
Thickener	39	117.46	45.81	
Total New Circuit			**588.81**	
	Fine Coal Cleaning and Dewatering Cost/ton of feed coal=		**$ 5.89**	
	Fine Coal Cleaning and Dewatering Cost/ton of clean coal=		**$ 9.65**	

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. A newly commercialized fine screening technology by Derrick Corporation, known as the Stack Sizer^{TM}, was successfully evaluated at a plant site using both 75-micron and 100-micron urethane mesh panels. High efficiency size separation, described by an *imperfection* value of 0.21 and ultrafine bypass of 4.72% at a d_{50c} of 76.7 microns, was achieved using a 75-micron (rectangular aperture) mesh panel. The corresponding efficiency measures for the 100-micron mesh panel were 0.27, 4.91%, and 98.2 microns, respectively. Sieve bends commonly used in coal preparation plants for fine coal screening were found to produce an *imperfection* value of 0.55, d_{50c} of 116.5 microns, and ultrafine bypass of 35.2%, which is a much inferior size separation performance.
2. Vibration frequency of the screen deck was the most important factor for effective separation size (d_{50c}) and *imperfection*, whereas feed flow rate affected ultrafine bypass the most for the Stack Sizer. Empirical models were successfully developed for the above mentioned three process responses as functions of vibration frequency, feed flow rate and wash water rate. F-ratio and R^2 values for all three models were less than 0.0001 and greater than 90%, respectively.

3. A new fine coal cleaning circuit consisting of a Stack Sizer and a Falcon Concentrator produced a clean coal product having a minimum ash content of 7.65% from a feed ash content of nearly 30%. This was the result of high efficiency size separation achieved at the Stack Sizer and high efficiency ash rejection achieved at the Falcon Concentrator when cleaning nominally +200-mesh coal.
4. A reasonably low 1.74 specific gravity of separation was achieved by the Falcon Concentrator along with a probable error (Ep) of 0.13 for cleaning nominally 16- X 200-mesh coal. However, 9.21% of the coarse clean coal was rejected to the tailings stream. This may indicate that the particle size range of 1-mm X 75 microns may be too wide to be cleaned by the Falcon Concentrator in a single stage fine coal cleaning circuit.
5. An economic analysis was conducted to compare the cost of fine coal cleaning and dewatering obtained by a traditional fine coal cleaning circuit consisting of classifying cyclones, spirals and flotation cells and the proposed circuit consisting of Stack Sizers and Falcon Concentrators. The estimated total cost per ton of feed coal for the traditional fine coal recovery circuit and the proposed new circuit were $4.93 and $5.89, respectively. However, it is believed that the significant reduction in sulfur penalty due to better pyrite rejection achievable by the proposed circuit may very well offset its higher cost of cleaning high sulfur coal on a per ton basis. The estimated payback periods for a traditional fine coal cleaning circuit and the proposed cleaning circuit are 17 and 22 months, respectively.

<u>Recommendations</u>

1. Considering the size separation performance achieved by the 75-micron mesh panel of the Stack Sizer and its impact on ash reduction, it is expected that the development of 52-micron mesh panel may significantly simplify the entire fine coal cleaning circuit of a modern day coal preparation plant for cleaning high sulfur coal. This may obviate the need for froth flotation cleaning of steam coal. Therefore, the main recommendation of this study is for Derrick Corporation and other industrial screen manufacturers to develop 270-mesh (52-micron) and possibly 325-mesh (44-micron) panels for the Stack Sizer.
2. With the development of finer mesh panels, a more effective fine coal cleaning circuit, consisting of Stack Sizer, Spiral and Falcon Concentrator can be developed and demonstrated, particularly for high sulfur Illinois coal.

ACKNOWLEDGEMENTS

Research funding received for this project from the ICCI through the Office of Coal Development and the Department of Commerce and Economic Opportunity is sincerely appreciated. The Principal Investigator greatly appreciates the support and guidance received from Derrick Corporation and Sepro Systems during the course of this investigation. Without the active support of Knight Hawk Coal Company and the plant personnel at the Creek Paum Mine, this work could not have been completed.

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