FINAL TECHNICAL REPORT
September 1, 2002, through October 31, 2003

Project Title: **EVALUATION OF A HIGH EFFICIENCY FINE COAL DEWATERING TECHNOLOGY**

ICCI Project Number: 02-1/4.1A-3
Principal Investigator: Dr. M. K. Mohanty, Southern Illinois University
Other Investigator: Mr. Zhigang Wang, Southern Illinois University
Project Manager: Mr. Joseph Hirschi, ICCI

ABSTRACT

A majority of coal preparation plants in Illinois continue to discard the minus 150 micron size fraction of their run-of-mine coal without any attempt to recover the clean coal present in this size fraction. This undesirable practice may be partly due to a variety of deficiencies with existing fine coal dewatering technologies, such as high moisture content of the product, loss of significant amounts of ultra-fine clean coal, high capital/operating costs and operational unfriendliness.

This research project investigated the suitability of a newly developed fine particle dewatering technology, known as Steel Belt Filter (SBF), for dewatering both fine clean coal and fine tailings materials generated at coal preparation plants in Illinois. The unique feature of this new technology is the simultaneous use of mechanical pressure and suction force (vacuum), which combination is known to provide excellent dewatering performance. Research personnel from ONDEO Nalco chemical company as well as SBF equipment vendors, Particle Separation Systems (PSS) of South Africa and Waltech Group of USA, actively participated in this investigation. A SBF prototype unit having a belt width of 0.6 m was tested at the Illinois Coal Development Park. A factorial experimental design using the response surface methodology was conducted to optimize the dewatering performance of the SBF prototype unit. Two different clean coal slurry samples having mean particle sizes of 400 micron and 50 micron and two fine coal tailings samples having mean particle sizes of 20 and 10 micron were dewatered using the SBF technology. A solid recovery of greater than 99% was achieved by using a suitable flocculant type and dosage for each sample. Surface moisture content of dewatered products varied from nearly 18.5% for coarser clean coal to 31% for finer clean coal and 18% for coarser tailings to 23% for finer tailings. The maximum product throughput achieved from the SBF prototype unit was nearly one ton per hour. A preliminary economic analysis conducted for a near-term commercialization of the SBF technology in the Illinois coal industry estimates the SBF dewatering cost to be $0.93/ton of dry coal product.

EXECUTIVE SUMMARY

The physical separation processes used for dewatering fine clean coal and tailings in coal preparation plants in Illinois include screen-bowl centrifuge, vacuum-disc filter, plate & frame filter press, and belt filter press. The screen-bowl centrifuge is most common due to its ability to produce low moisture content, relative ease of operation and maintenance, relatively low operating and capital cost, and high throughput capacity. However, it is also very well known that a significant amount of valuable ultra-fine (minus 45 micron) clean coal is either lost to the main effluent or continuously recirculated in the screen-drain stream, which reduces the fresh feed throughput capacity of the screen-bowl centrifuge. Filtration dewatering processes, especially the vacuum disc filter, are typically selected over the screen-bowl centrifuge in the presence of relatively large proportion of ultra-fines (minus 45 micron) to achieve high solid recovery at reasonably low product moisture content. However, the capital and operating costs of disc filters are significantly higher than that of screen-bowl centrifuges having the same throughput capacity. The plate & frame filter presses are used mostly in cases of extremely fine size coal or tailings material. However, the requirement of extremely high capital and operating costs often render this process cost-prohibitive for steam coal applications. Belt filter presses are used with limited success in coal preparation plants for dewatering fine tailings material. High product moisture content, relatively high solids content of the filtrate and mechanical complexities are some of the problems associated with belt filter presses.

A new filtration technology, known as PSS™ Steel Belt Filter (SBF), has recently been patented in South Africa to overcome some of the deficiencies of the conventional fine coal dewatering technologies discussed in the aforementioned paragraph. The SBF technology utilizes vacuum, double-deck stainless steel belts and a hot air system (optional feature) to achieve very low moisture contents and high solid recovery even in the presence of high amount of ultra-fine materials with the use of a small amount of flocculant. A venturi system is utilized to create high flow and variable vacuum systems to facilitate effective dewatering of coal fines. The main objective of this research project was to determine the effectiveness of SBF technology for dewatering Illinois coal fines, both clean coal and tailings materials.

A SBF prototype having a belt diameter of 0.6 meter was tested at the Illinois Coal Development Park using clean coal and tailings samples having varying particle size distribution. The four coal samples tested in this investigation were collected from three different coal preparation plants in Illinois. The clean coal samples included a flotation product sample having a mean particle size of 50 micron and an ash content of 6.20% and a combined spiral+flotation product sample having a mean particle size of 400 micron and an ash content of 19.2%. The tailings samples included a spiral tailings material having a mean particle size of 20 micron and an ash content of 36% and a high-ash thickener underflow sample having a mean particle size of 10 micron and an ash content of nearly 60%. However, a majority of the SBF experiments including the process optimization tests were conducted using the combined spiral+flotation product.

Determination of a suitable flocculant type and dosage for the multiple coal samples was initially a great challenge, eventually solved with assistance of ONDEO Nalco Company personnel. After testing the coal samples in their laboratory, the Nalco Company personnel recommended three anionic, one cationic and one neutral dewatering aid to be tested with the SBF technology. One more set of anionic and cationic flocculants obtained from yet another chemical company was also used in this study. Several series of exploratory tests were conducted to determine a suitable flocculant type or types for each coal sample. A three factor-level Box-Behnken design was conducted to obtain the highest solid recovery at the lowest possible product moisture content by varying four key process parameters: belt speed, volumetric feed flow rate, feed solids content and flocculant dosage.

Solid recovery was extremely low in the absence of a suitable flocculant type and dosage. However, by selecting the appropriate flocculants for each coal sample, a solid recovery of greater than 99% was achieved in each case. The lowest surface moisture content of the dewatered products varied from nearly 18.5% for the combined spiral+flotation product sample to 31% for flotation product sample and from 18% for spiral tailings to 23% for the thickener underflow materials. The maximum product throughput achieved from the SBF prototype unit was nearly one ton per hour (tph).

A preliminary economic analysis was conducted using the relevant technical data generated during this investigation and the capital and operating cost data obtained from the parent equipment company in South Africa. It was estimated that a full-scale SBF unit having a belt width of 2.5 meters and a product throughput capacity of nearly 20 tph would result in a dewatering cost of $0.93/ton of dry coal product. Such low dewatering cost along with a maximum flotation cost of nearly $1.50/ton may allow fine coal cleaning and dewatering to be extremely profitable. An on-site investigation to study the effectiveness of the SBF technology in a real plant environment is recommended as the next step for expediting commercialization in coal preparation plants in Illinois.

OBJECTIVES

The overall goal of the research program was to prove that the Steel Belt Filter (SBF) technology can effectively dewater fine clean coal and fine tailings material from coal preparation plants in Illinois. The specific research objectives were:

- To optimize the performance of the SBF technology for dewatering fine clean coal of nominally minus 1 mm and minus 100 mesh size class and achieve a surface moisture content of less than 20% while recovering more than 95% solids.

- To dewater the preparation plant fine refuse generating in the form of thickener underflow and achieve surface moisture content of less than 30%.

- To conduct an economic analysis to determine the fine coal dewatering cost (both capital and operating) on a per ton basis.

INTRODUCTION AND BACKGROUND

Over the years, researchers at Southern Illinois University and the Illinois State Geological Survey have successfully conducted several pilot-scale and in-plant studies proving the effectiveness of a variety of advanced flotation and enhanced gravity separation technologies with direct funding from ICCI/DCEO. However, actual commercialization of these technologies in Illinois coal preparation plants has been limited. Based on discussions with many plant personnel, it is understood that one of the main reasons behind the indifference of plant operators towards state of the art fine coal cleaning technologies is the associated dewatering and handling difficulty of resulting fine coal concentrate. In the absence of a fine (i.e., minus 150 micron) coal cleaning circuit, a majority of the coal preparation plants in Illinois have been utilizing the screen-bowl centrifuge for dewatering 1 mm x 150 micron size clean coals. The wide use of a mechanical dewatering process such as screen-bowl centrifugation is a result of its ability to produce low moisture content, relative ease of operation and maintenance, relatively low operating and capital cost, and high throughput capacity. However, it is also well known that with the existing screen-bowl design, a significant proportion of the ultra-fine (i.e., minus 45 micron) coal is lost to the centrate. Some recent research findings of the Principal Investigator indicate that the clean coal loss is quite significant if the proportion of the minus 45 micron size particle coal is more than 20%.

Filtration is a solid-liquid separation process where solid particles are separated from the liquid by forcing the slurry to pass through a suitable filtering medium on which the solids build up. The driving force for the slurry to pass through the filter medium is created by either pressure (e.g. plate & frame filter press and belt press) or vacuum (e.g. vacuum drum filter, disk filter and horizontal belt filter). Most of the filtration processes are known for their high solid recovery at reasonably low moisture content. While maintaining the filter medium (cloth or plastic) is a common problem with both pressure and vacuum filtration processes, high flocculant cost required for vacuum filters and excessively high capital costs of pressure filters are the major deterrents to the use of commercially available filtration technologies. Most of these problems have been overcome in the Steel Belt Filter (SBF) technology recently patented by Particle Separation Systems (PSS) of South Africa.

As shown in Figure 1, the PSS^{tm}-SBF unit consists of two special woven steel mesh belts rotating at the same speed with the top belt in the anti-clockwise and bottom belt in the clock-wise direction. The feed slurry is introduced evenly on the bottom belt by a feed distributor so that the entire width of the belt is covered with the slurry. Before being pressed between the two belts, the slurry material is pre-dewatered by vacuum boxes placed underneath the bottom belt. The thickened slurry is then subjected to mechanical pressure being sandwiched between the two belts through a series of offset top and bottom rollers. Water is withdrawn from the solid material under the simultaneous action of mechanical pressure, suction force provided by vacuum boxes as well as hot air if necessary.

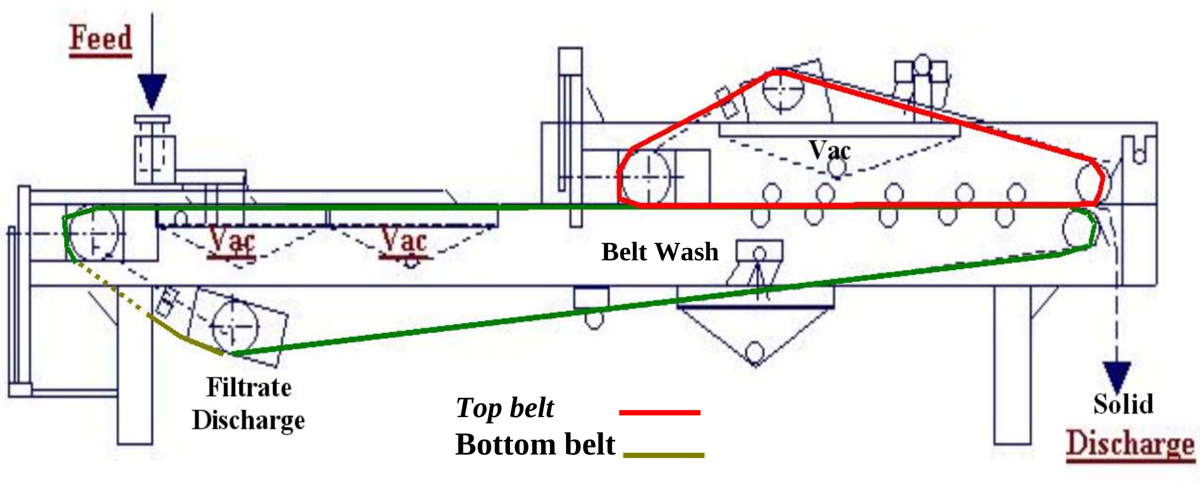


Figure 1: Schematic diagram of the PSS^{TM}-Steel Belt Filter (PSS website, 2002)

Thus, SBF technology combines the dewatering action of two conventional dewatering technologies; i.e., horizontal vacuum belt filter and conventional belt filter presses, into one novel system. Some of the unique features of the SBF technology may be summarized as follows:

- The use of woven mesh steel belt for dewatering application in contrast to plastic belts is unique; along with a superior locking mechanism at the belt joints, the steel belt increases the mechanical strength of the belt ten-fold. Thus, the ability to accidentally handle large objects, such as lumps in a plant environment, is far easier with the steel belts. In addition, the drainage rate of steel belts are known to be twice that of plastic belts due to the availability of more open area in a woven mesh steel belt and the hydrophilicity of plastic.

- Use of vacuum for pre-dewatering followed by the application of mechanical pressure to achieve the final dewatering of the feed slurry may produce the minimum possible moisture content. The inventor, Mr. Rein Buisman, has reported the achievement of as low as 19 to 20% product moisture content while dewatering plant fine tailings having nearly 90% of minus 325 mesh materials with a pilot-scale SBF unit. The presence of only 1 to 2% solid in the filtrate may be considered as very good filtrate-clarity.

- Although steel belts cost nearly 50% more than plastic belts, the longer life of steel belts offsets the higher belt cost. The other advantage of using steel belts is in the case where extremely dry product is required; in such case, a hot air system may be used which may raise the temperature of the steel belt up to 212^0 F without affecting the belt material. This is not possible with plastic belts.

- The capital and operating cost of a full-scale SBF system is projected to be lower in comparison to many of its competing technologies due to the simplicity of the unit, with significantly less power consumption in comparison to belt presses and lower flocculant costs in comparison to vacuum filters and horizontal belt filters.

This study aimed at investigating the suitability of SBF technology for dewatering both clean coal fines and fine tailings material generated at coal preparation plants in Illinois. An economic analysis has also been conducted in consultation with the equipment manufacturer to estimate the dewatering cost (both capital and operating) on a per ton basis. The results of these technical and economic evaluations are the subject matter of this report.

EXPERIMENTAL PROCEDURES

Initial experiments conducted using the SBF pilot-scale unit utilized a closed circuit so that the dewatered product and the filtrate effluents were mixed together in a tank and continuously recirculated as illustrated in Figures 2 and 3. This type of circuit arrangement allowed conducting several rounds of exploratory tests to become familiar with the basic operation of the unit and establishing base line test conditions at the expense of a limited amount of coal slurry.

The dewatering circuit consisted of a feed sump and pump assembly equipped with an on-line slurry flow meter, a SBF prototype unit and a recirculation tank and pump assembly. The compressed air system used to provide sufficient air for the venturi-vacuum system and also the diaphragm pumps is not shown in the circuit-layout. On an experimental day, the feed sump was filled with nearly 150 gallons of coal slurry having the desired solid content. When flocculants were required, a calculated amount of the desired flocculant is added directly to the feed tank. A diaphragm pump was used to feed the coal slurry to the SBF unit at a desired flow rate. Prior to the introduction of the feed slurry, checks were made to be sure that the belts were properly cleaned and set in motion at the desired speed. The liquid effluents were collected separately from the vacuum section and mechanical pressure section of the belt whereas the relatively dry solid was discharged at the delivery end.

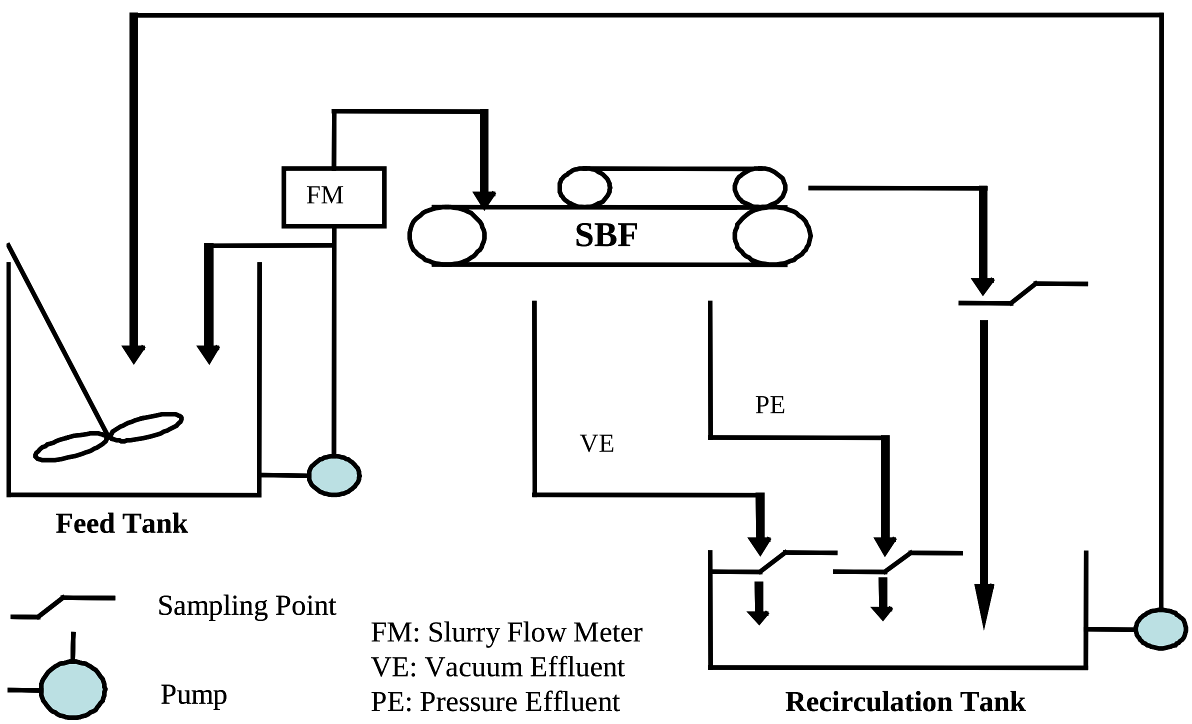


Figure 2: A schematic layout of the fine coal dewatering circuit used for the initial SBF experiments

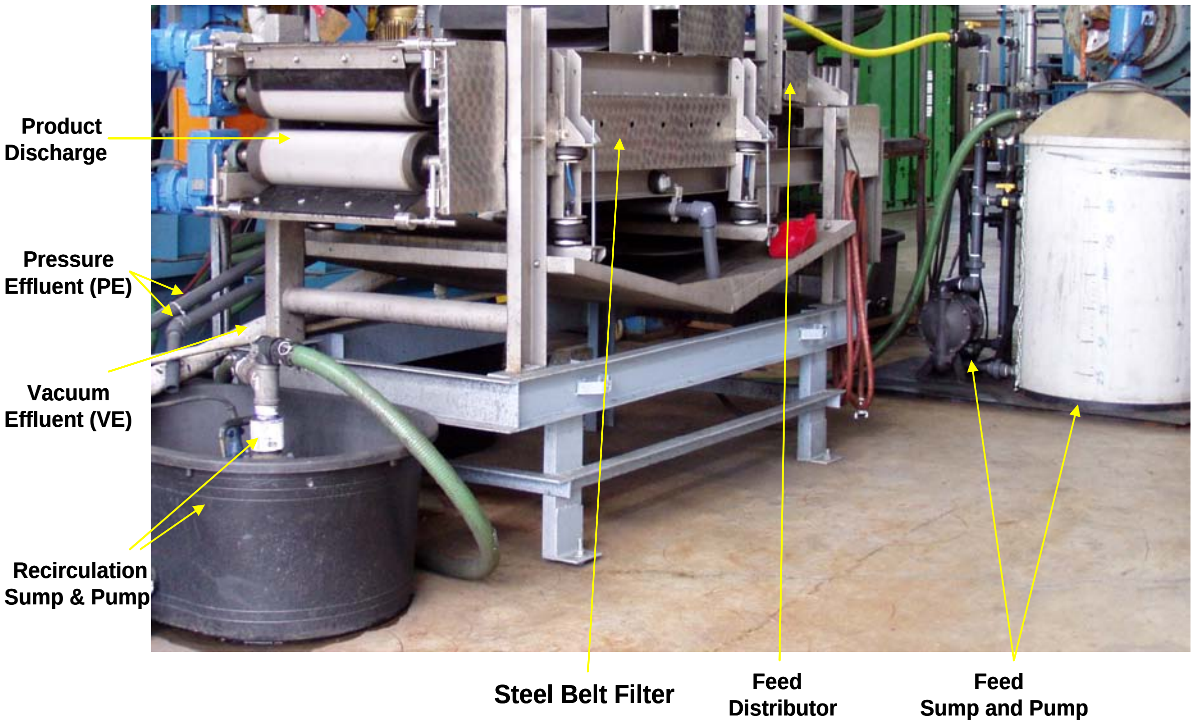


Figure 3: The SBF prototype tested at the Illinois Coal Development Park

Independent samples were collected from each stream as indicated in the circuit-layout. All three streams were mixed together in the recirculation tank, which was equipped with a compressed air operated mixing system to minimize the settling of solids in the tank. The well-mixed slurry was continuously pumped using a submersible pump to the feed tank to allow a continuous supply of feed material to enable a longer period of testing.

After the initial experimental phase was over, arrangements were made for the on-line addition of flocculant for a more effective flocculating action. As shown in the modified circuit-layout in Figures 4 and 5, a static-mixer was connected in the feed line for proper mixing of the flocculant in the feed slurry. Based on the recommendation of research personnel from ONDEO Nalco Company, the anionic flocculant was added to the feed slurry prior to the static mixer, whereas the cationic flocculant was added after the static mixer. For clean coal dewatering, a medium molecular weight anionic polymer provided the required flocculating action. However for the tailings materials, a high molecular weight anionic polymer along with a cationic polymer was required for sufficient flocculating action. As shown, the recirculation arrangement was completely removed. On each experimental day, a fresh batch was mixed in the feed sump and water was added to obtain the desired solid content in the feed slurry. The desired flocculants were added using peristaltic pumps as shown in Figure 5.

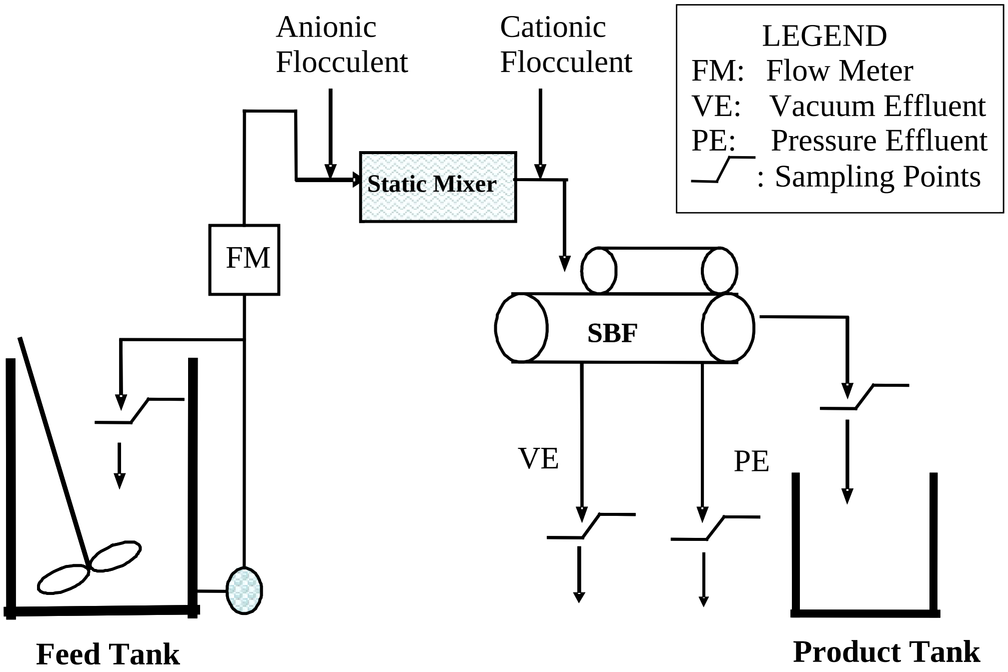


Figure 4: A schematic of the modified circuit layout

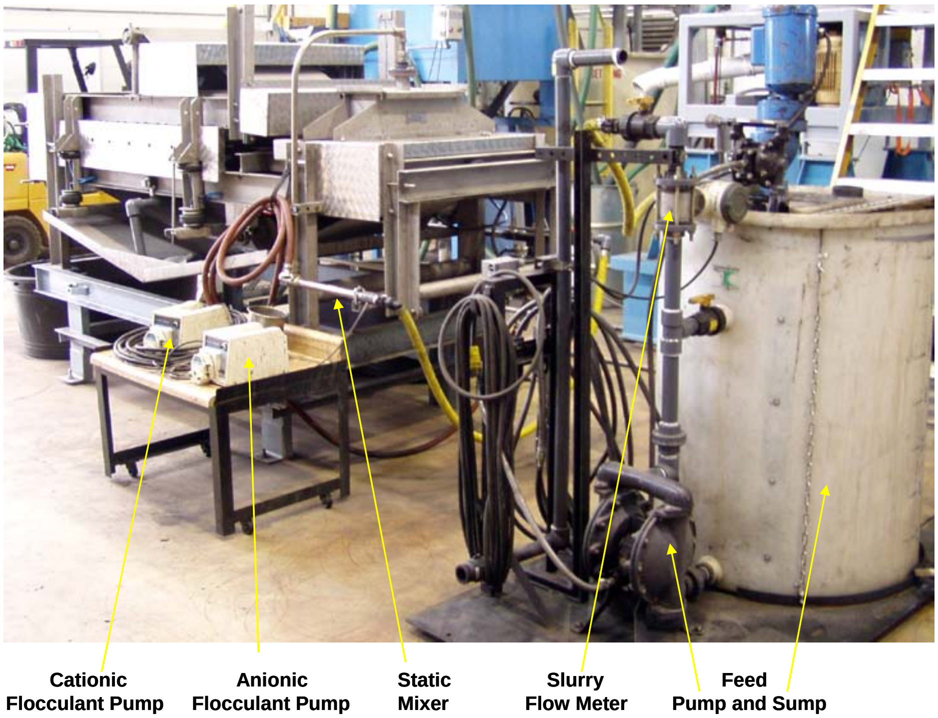


Figure 5: A photograph showing the modified circuit

RESULTS AND DISCUSSIONS

This project was divided into six research tasks to achieve the specific objectives and the overall goal of this investigation.

Task 1: Sample Collection and Characterization

Fine coal slurry samples were collected from three preparation plants to be used in this investigation. Flotation product and thickener underflow samples were collected from two separate plants and fine raw coal cyclone feed slurry was collected from a third plant. The raw coal cyclone feed was cleaned with an industrial size coal spiral at the Illinois Coal Development Park to produce a clean coal product and tailings. Subsequently, the spiral product sample was mixed with a portion of the flotation product sample at a ratio of 2:1 to prepare the dewatering feed slurry to be used for the majority of the SBF tests. In total, four coal slurry samples were either collected or prepared for the SBF experiments. The size-consist of each of these samples, plotted in Figure 6, indicates the wide range of feed size distributions tested. The mean particle sizes for the four samples tested are 400 micron, 50 micron, 20 micron and 10 micron, respectively. The minus 45 micron size particle content of each sample was 14%, 25%, 60% and 71%, respectively. The clean coal samples had ash contents of 19.2% and 6.2%, respectively, whereas the ash contents for the tailings samples were 36% and 60%, respectively.

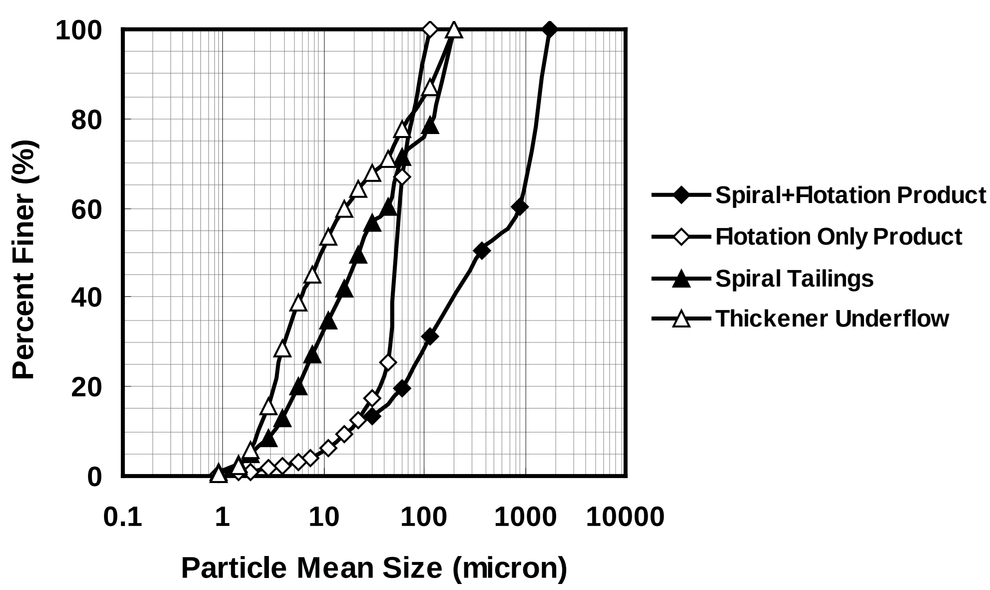


Figure 6: Size consists of the four coal samples tested

Task 2: Installation of the SBF prototype at the High-bay Research Facility

A SBF prototype unit was purchased from the Waltech Group at a discounted price to be used for this investigation. However, delivery of the SBF unit at the Illinois Coal Development Park was significantly delayed by the equipment vendor due to reasons beyond their control. Therefore, a 2-month no-cost extension was required for the successful completion of this project.

A photograph of the as-delivered SBF unit is shown in Figure 7. The compressed-air line supplied with the unit for the vacuum system was too small and had to be replaced by a line of appropriate size. An airflow meter was also connected to get an on-line measurement of the volumetric flow rate and pressure of air supplied to the vacuum system of the unit. As previously shown in Figures 3 and 5, a 2 ft high steel frame was built for the SBF unit to place the discharge end at an adequate height for easy collection of test samples and also for maintenance of the unit. A pump and sump assembly was prepared specifically for the SBF operations using a PVC tank having a maximum capacity of 180 gallons and a diaphragm pump. An air-compressor having a capacity of producing more than 1000 scfh of air at nearly 90 psi of pressure was connected to the SBF circuit to provide sufficient air through the venturi-tube of the vacuum system.

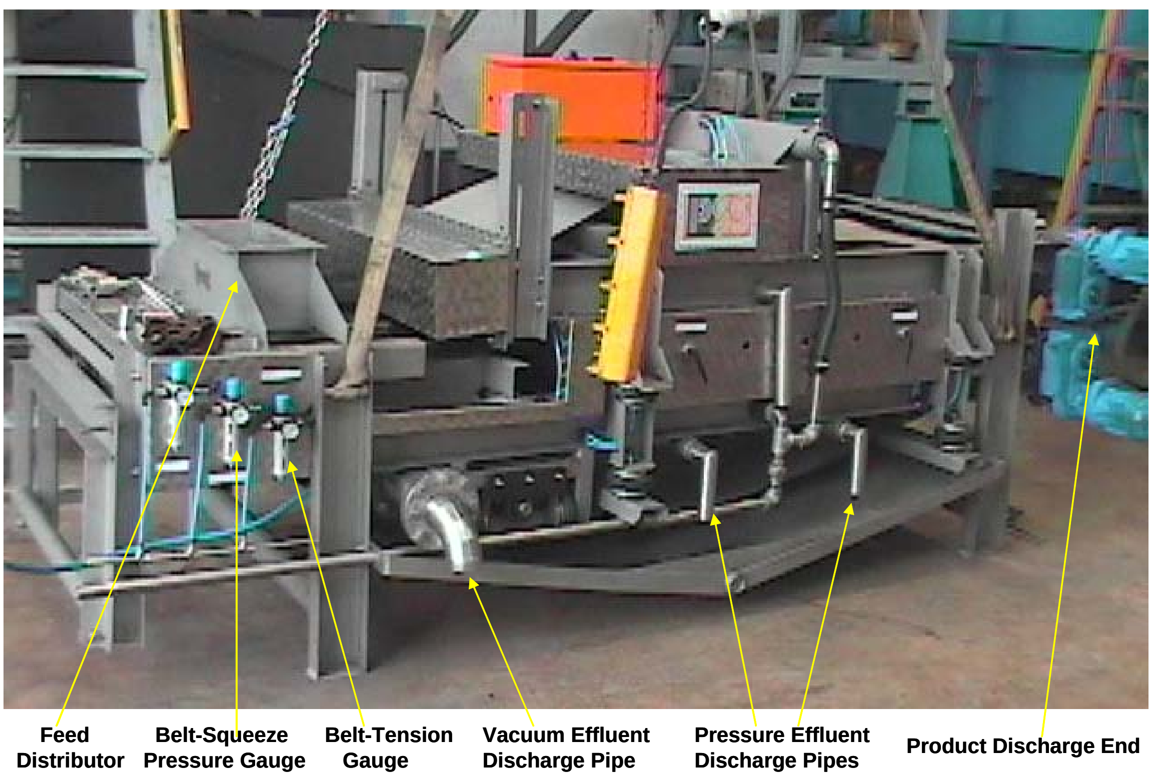


Figure 7: A picture of the just-delivered SBF unit at the high-bay research facility of the Illinois Coal Development Park

Task 3: SBF Testing for Dewatering Fine Clean Coal Concentrate

Task 3.1 Exploratory Test Program: The initial tests using the SBF prototype unit were conducted to become familiar with its operation and get some understanding of the effects of the physical process parameters, such as lift (belt squeeze) pressure and belt speed. Based on the experimental data plotted in Figure 8, lift pressure was set at 6 bar (88 psi) for subsequent SBF tests. Belt speed affects the residence time of coal slurry on the belt and the amount of time it is subjected to vacuum. Therefore, moisture content of the product reduces with decreasing belt speed. However, the feed throughput capacity of the SBF unit also reduces with decreasing belt speed. Thus, belt speed was considered as one of the process parameters to be further studied. Although, reasonable product moisture contents were achievable, the highest solid recovery obtained without the use of any flocculant was only 74%. Thus, subsequent SBF tests were conducted using various flocculants to improve solid recovery above the target level of 95%.

Several flocculant types including two anionic polymers, one cationic polymer and one newly developed neutral dewatering aid were tested in the subsequent round of tests. The details of the operating parameters, flocculants used and the results are summarized in Table 1, which indicates only a few tests with high solid recovery values. The experimental layout previously shown in Figure 2 was used until this point in the test program. Based on the recommendations of the research personnel from the ONDEO Nalco Company, the SBF circuit layout was modified to facilitate on-line addition of the flocculants as shown in Figure 4. A significant improvement in solids recovery is quite evident at even low flocculant dosage of 0.1 to 0.2 lb/ton, as shown in the experimental results summarized in Table 2. Two more anionic flocculants, one more cationic flocculant and one surfactant were tested to achieve the lowest possible product moisture contents while achieving a solid recovery of 99% or greater.

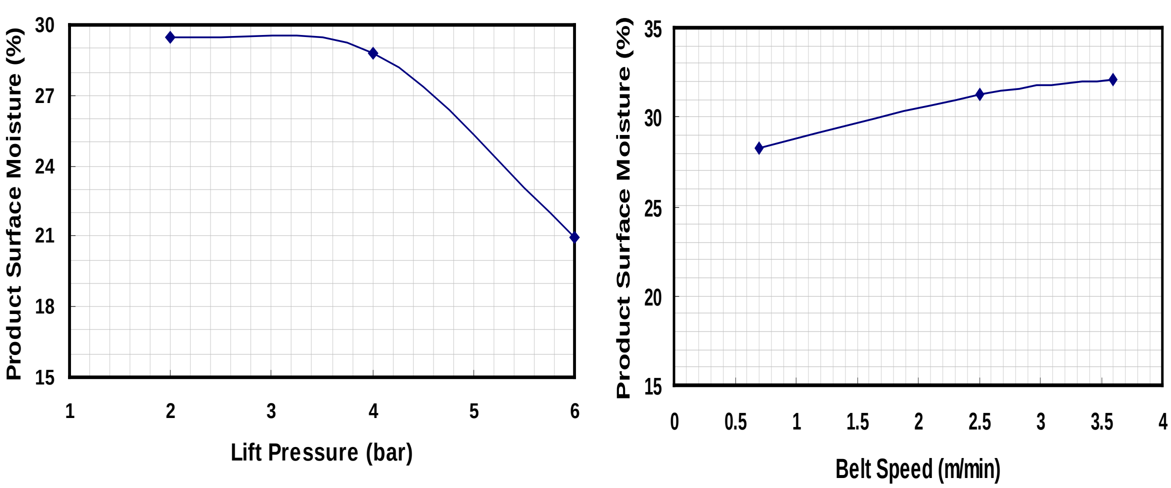


Figure 8: Preliminary SBF test data showing the effects of lift pressure and belt speed on moisture content of the dewatered product

Table 1: Operating parameters used and test results obtained from the first round of exploratory tests

Test #	Operating Parameters							Results						
	Feed Flow		Belt Speed	Lift Pressure	Chemcials Used (lb/ton)			Vacuum Effluent		Pressure Effluent		Solid Recovery	Product Moisture(%)	
	(lpm)	(% solid)	(m/min)	(bar)	Cationic	Anionic	Others	(lpm)	(% solid)	(lpm)	(% solid)	(%)	Total	Surface
1	12	30	0.7	6			0.0	4.98	24.9	3.30	24.64	44.94	30.09	22.09
2	12	30	0.7	6			0.5	5.10	22.6	3.30	23.73	48.14	30.42	22.42
3	12	30	0.7	6			1.0	6.30	23.0	4.50	24.22	31.86	32.32	24.32
4	12	30	0.7	6			1.0	5.52	21.7	3.84	24.37	42.84	31.15	23.15
5	12	30	0.7	6			2.0	6.60	23.1	2.40	22.55	44.57	32.60	24.60
6	12	30	0.7	6			2.0	5.70	22.1	2.70	23.51	49.27	31.35	23.35
7	12	30	0.7	6			4.0	5.40	20.7	3.30	21.79	49.32	32.67	24.67
8	12	30	0.7	6			4.0	5.40	20.1	3.36	23.89	47.94	33.19	25.19
9	21	30	0.7	6			4.0	7.92	24.2	9.12	24.47	34.68	32.44	24.44
10	10	40	2.0	6		0.00		8.70	33.5	4.50	35.64	32.21	38.20	30.20
11	10	36	2.0	6		0.05		5.10	26.9	5.10	33.53	22.86	39.15	31.15
12	10	34	2.0	6		0.10		3.00	14.0	2.28	20.33	76.56	40.18	32.18
13	10	33	2.0	6		0.15		3.48	8.99	6.48	25.69	46.01	36.00	28.00
14	10	31	2.0	6		0.20		3.90	9.40	6.90	24.89	39.45	37.19	29.19
15	20	31	3.4	6		0.20		8.28	21.3	10.20	28.65	29.61	38.21	30.21
16	15	31	3.4	6		0.20		6.18	19.2	6.60	29.79	35.08	41.11	33.11
17	15	28	2.6	6		0.30		4.56	6.12	5.16	25.22	67.48	35.07	27.07
18	15	22	2.6	6		0.40		6.00	20.3	5.70	27.94	42.16	38.41	30.41
19	15	27	2.6	6	0.20	0.50		4.80	11.3	6.90	23.32	55.76	37.78	29.78
20	10	25	0.7	6	0.00	0.00		5.10	7.15	1.80	6.81	82.45	32.99	24.99
21	10	10	0.7	6	0.00	0.30		7.50	7.79	1.86	0.98	78.28	36.14	28.14
22	10	10	0.7	6	0.50	0.40		8.28	0.07	1.68	0.14	99.71	34.41	26.41

From Test 1 to 9; Chemcials used were MCT TX11750
From Test 10-19: Chemicals used were TX12417 (Anionic) + TX12437 (Cationic)
From Test 20-22: Chemicals used were TX12436(Anionic) + TX12437 (Cationic)

Table 2: Operating parameters used and test results obtained from the second round of exploratory tests

Test #	Operating Parameters							Results						
	Feed Flow		Belt Speed	Lift Pressure	Chemcials Used (lb/ton)			Vacuum Effluent		Pressure Effluent		Solid Recovery	Product Moisture (%)	
	(lpm)	(% solid)	(m/min)	(bar)	Cationic	Anionic	Others	(lpm)	(% solid)	(lpm)	(% solid)	(%)	Total	Surface
1	15	30	1.3	6		0.1		6.2	0.74	1.6	0.64	98.88	28.22	20.22
2	15	30	1.3	6		0.2		6.2	0.50	2.4	0.13	99.32	29.09	21.09
3	15	30	1.3	6		0.4		5.4	1.22	3.2	0.19	98.56	29.57	21.57
4	15	30	1.3	6		0.7		4.2	0.74	4.4	0.65	98.81	31.52	23.52
5	15	30	1.3	6	0.05	0.1		7.5	0.33	3	0.44	99.23	29.80	21.80
6	15	30	1.3	6	0.10	0.2		6.9	0.04	2.8	0.05	99.92	31.16	23.16
7	15	30	1.3	6	0.20	0.4		5.4	0.20	4.2	0.04	99.74	31.45	23.45
8	15	30	1.3	6	0.30	0.6		4.8	0.39	5.6	8.53	89.79	32.90	24.90
9	15	30	1.3	6		0.2		7.8	0.22	2	0.27	99.55	33.97	25.97
10	15	30	0.68	6		0.2		4.5	0.11	1.6	0.11	99.87	29.63	21.63
11	15	30	0.68	6		0.2		7.2	0.15	2.2	0.29	99.65	31.86	23.86
12	15	30	1.3	6		0.2		6.3	0.16	2	0.17	99.73	33.10	25.10
13	10	30	1.3	6		0.2		7.5	0.06	3	0.19	99.70	30.81	22.81
14	20	30	1.3	6		0.2		7.8	0.32	2.4	0.12	99.58	30.96	22.96
15	10	30	1.3	6		0.2		6.3	0.12	1.8	0.20	99.65	30.71	22.71
16	15	30	0.68	6		0.2		4.8	0.26	1.2	0.07	99.73	31.66	23.66
17	20	30	0.68	6		0.2		4.5	0.16	1.68	0.32	99.80	35.52	27.52
18	15	30	1.3	6		0.2		6.6	0.09	2.6	0.13	99.82	33.68	25.68
19	15	30	1.3	6		0.2		7.5	0.14	2.6	0.10	99.74	31.59	23.59
20	15	27	1.3	6		0.2		8.7	0.01	3.2	0.04	99.95	33.89	25.89
21	15	30	1.3	6		0.2	0.10	6.9	0.27	2.2	0.25	99.52	31.57	23.57
22	15	30	1.3	6		0.2	0.10	7.5	0.27	2.2	0.25	99.49	31.07	23.07
23	15	30	1.3	6		0.1	0.05	6.9	0.70	2.28	1.00	98.58	31.92	23.92
24	15	30	1.3	6		0.1	0.05	7.0	0.78	1.88	0.99	98.55	31.28	23.28
25	15	30	1.3	6		0.2	0.10	6.9	8.50	2	8.51	84.85	35.18	27.18
26	15	30	1.3	6		0.2	0.10	6.6	8.68	2.08	9.85	84.42	35.75	27.75
27	15	30	1.3	6	0.05	0.1		7.5	0.37	2.28	0.59	99.16	30.95	22.95

Tests 1-4; Chemcials used were TX12417(Anionic);Tests 5-8, TX12436(Anionic) + TX12437 (Cationic);
Tests 9-14: Chemicals used were TX12417 (Anionic); Tests 15-20:TX12436 (Anionic); Tests 21-24: TX12436 (Anionic) + TX12523 (Surfactant);
Tests 25-26: Chemicals used were TX12524 (Anionic) + TX12523 (Surfactant); Tests 27: Cheimcals used were 2640 (Anionic) + 40176 (Cationic)

Task 3.2: Optimization Test Program: Based on the exploratory test programs, a medium molecular weight anionic polymer, commercially known as TX 12417, was selected for use in the optimization test program. Three other process parameters including feed solid content, volumetric feed flow rate and belt speed were selected for further investigation during this research task. Based on the results obtained from the exploratory test program it was decided to maintain the lift (belt squeeze) pressure constant at 6 bar (88 psi) during the entire test program. A test matrix of 29 tests was prepared using the Box-Behnken experimental design to conduct a detailed parametric study and develop an empirical model to predict the surface moisture content as a function of the aforementioned four key process parameters. As indicated in Table 3, the solid recovery values for all 29 tests were above 98.5%, which is considered as an excellent achievement for any filtration dewatering process using only 0.1 lb/ton of flocculant. The product samples were analyzed for their total moisture content using a drying oven. The surface moisture content for each sample was calculated by subtracting the inherent moisture content of 8% for the given coal. The data shown for Test 15 in Table 3 indicates the lowest surface moisture content of 20.3% that was achieved at an excellent solid recovery of 99.9%. The total range of surface moisture contents varied from 20.3% to a maximum of 33.5% for the 25 different operating conditions used during the optimization experimental program. A mean moisture content of 24% with a standard deviation of only 0.84% obtained from the five tests conducted using the medium levels for each parameter is indicative of the great repeatability of the test data.

Parametric study: An empirical model was developed to obtain a better understanding of parameter main and interaction effects on the surface moisture content of the SBF dewatered product. The model equation is expressed as follows:

$$SM = 60.5 + 4.38BS - 2.1FS + 0.033FS^2 - 0.38FR - 38.6FL + 1.40FR*FL \qquad [1]$$

where SM = surface moisture (%)
BS = belt speed (m/min)
FS = feed solid content (% by weight)
FR = volumetric feed flow rate (liters per minute; lpm)
FL = flocculant dosage (lb/ton)

The model equation clearly reveals that product moisture increases with increasing belt speed. This prediction agrees well with the experimental results illustrated previously in Figure 8. However, the exact relationship of product moisture content with the other SBF parameters is not quite clear. For example, in the model equation, FS (feed solid content) has a negative sign; but FS^2 has a positive sign. Hence it is not clear whether surface moisture content increases or decreases with increasing feed solid content. The main effects of feed solid content and the respective interaction effects are explained in Figures 9 (a-c). As shown, the surface moisture of the SBF product gradually decreases as the feed solid content is increased from 18% solid to around 32%; beyond this point the effect is insignificant up to the maximum solid content of 36% studied during this investigation. The parallel relationships in all three cases are indicative of the

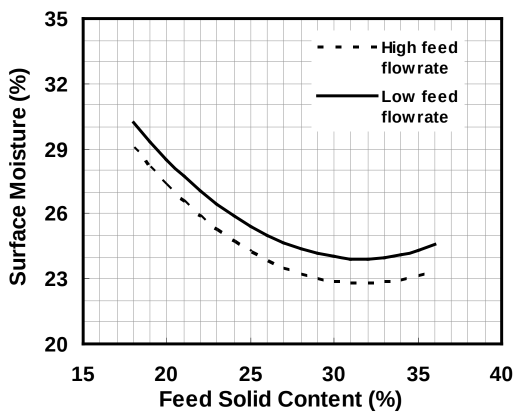
Table 3: The details of the operating parameters used and test results obtained from the optimization test program.

Test #	Operating Parameters							Results						
	Feed Flow		Belt Speed	Lift Pressure	Chemcials Used (lb/ton)			Vacuum Effluent		Pressure Effluent		Solid	Product Moisture(%)	
	(lpm)	(% solid)	(m/min)	(bar)	Cationic	Anionic	Others	(lpm)	(% solid)	(lpm)	(% solid)	Recovery (%)	Total	Surface
1	24	27	2.1	6		0.2		13.20	0.14	3.84	0.30	99.6	29.63	21.63
2	24	36	1.4	6		0.2		9.60	0.18	2.52	0.32	99.7	30.84	22.84
3	18	27	1.4	6		0.2		7.50	0.08	1.86	0.18	99.8	32.31	24.31
4	24	27	1.4	6		0.2		8.40	0.13	1.98	0.03	99.8	31.75	23.75
5	18	27	1.4	6		0.1		7.80	0.07	2.08	0.01	99.9	31.01	23.01
6	18	18	0.7	6		0.2		8.64	0.09	1.80	0.09	99.7	33.42	25.42
7	18	36	1.4	6		0.3		7.20	0.14	2.00	0.21	99.8	31.33	23.33
8	18	18	2.1	6		0.2		12.60	0.22	1.80	0.14	99.1	41.51	33.51
9	18	27	1.4	6		0.2		9.90	0.06	2.48	0.03	99.9	31.58	23.58
10	24	18	1.4	6		0.2		13.20	0.23	3.20	0.67	98.8	38.33	30.33
11	18	27	0.7	6		0.3		7.20	0.04	1.76	0.00	99.9	28.88	20.88
12	18	27	0.7	6		0.1		7.20	0.03	1.60	0.00	99.9	30.11	22.11
13	12	27	2.1	6		0.2		6.00	0.09	1.32	0.10	99.8	36.23	28.23
14	18	36	1.4	6		0.1		9.00	0.47	1.76	0.38	99.3	33.11	25.11
15	24	27	0.7	6		0.2		8.40	0.05	1.88	0.01	99.9	28.31	20.31
16	12	27	0.7	6		0.2		5.70	0.13	1.40	0.09	99.8	31.40	23.40
17	18	36	2.1	6		0.2		8.10	0.26	2.20	0.14	99.7	35.92	27.92
18	18	27	2.1	6		0.1		9.00	0.29	2.00	0.23	99.4	36.23	28.23
19	24	27	1.4	6		0.3		11.40	0.11	3.76	0.18	99.7	30.53	22.53
20	18	27	2.1	6		0.3		8.70	0.14	2.20	0.20	99.7	32.96	24.96
21	12	18	1.4	6		0.2		9.30	0.31	1.08	0.52	98.5	37.17	29.17
22	12	27	1.4	6		0.2		7.20	0.19	1.60	0.14	99.6	34.28	26.28
23	18	36	0.7	6		0.2		7.50	0.10	1.52	0.03	99.9	28.50	20.50
24	12	27	1.4	6		0.3		7.20	0.11	1.60	0.16	99.7	29.69	21.69
25	12	36	1.4	6		0.2		5.58	0.22	1.32	0.11	99.7	32.43	24.43
26	18	27	1.4	6		0.2		9.72	0.08	2.20	0.36	99.7	31.93	23.93
27	18	27	1.4	6		0.2		9.30	0.11	2.60	0.18	99.7	33.26	25.26
28	18	18	1.4	6		0.3		10.80	0.12	2.92	0.14	99.5	35.62	27.62
29	18	18	1.4	6		0.1		12.00	0.09	1.80	0.21	99.6	39.57	31.57

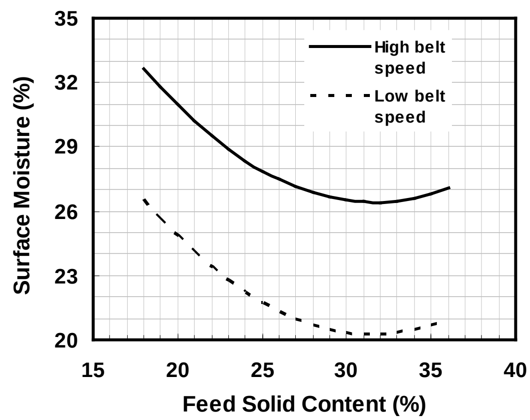
In all 29 tests, the flocculant used was TX12417 (Anionic) insignificant effect on surface moisture from feed solid-feed flow rate, feed solid-belt speed and feed solid-flocculant dosage interactions.

As illustrated in Figures 10 (a-b), feed flow rate has a marginal effect on SBF product moisture content; however, feed flow rate-flocculant dosage interaction has a greater effect. The dramatic effect of on-line addition of a suitable flocculant on the solid recovery was previously explained in another section; the effect of flocculant dosage on surface moisture is illustrated in Figure 10 (c). The moisture content is reduced by nearly

(a)



(b)



(c)

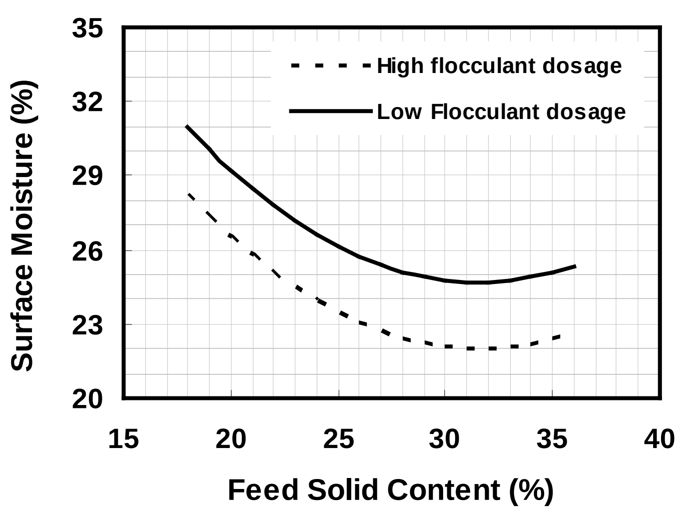
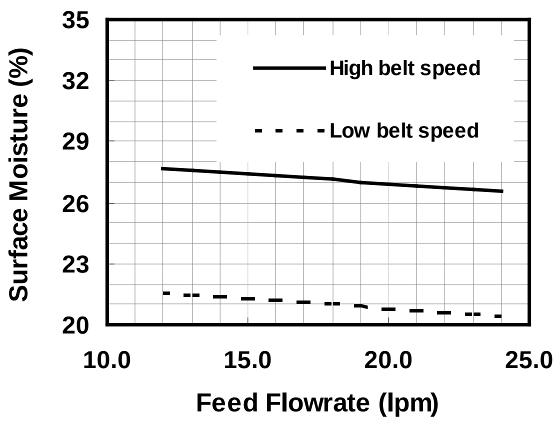


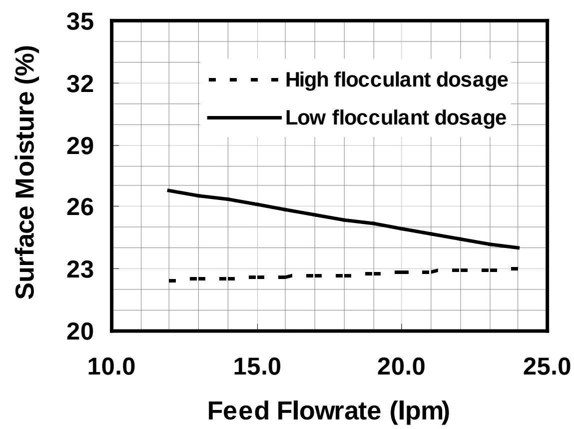
Figure 9: Illustration of the main effect of feed solid content and the effects of feed solid-feed flow rate, feed solid-belt speed and feed solid-flocculant dosage interactions on SBF moisture content

2.5 % with an increase in flocculant dosage from 0.1 to 0.3 lb/ton. However, since use of more flocculant adds significantly to the dewatering cost, high flocculant dosage may not be a desirable option most of the time. Although, there was clearly an effect of flocculant dosage-feed flow rate interaction, the effect of flocculant dosage-belt speed interaction does not appear to be significant.

(a)



(b)



(c)

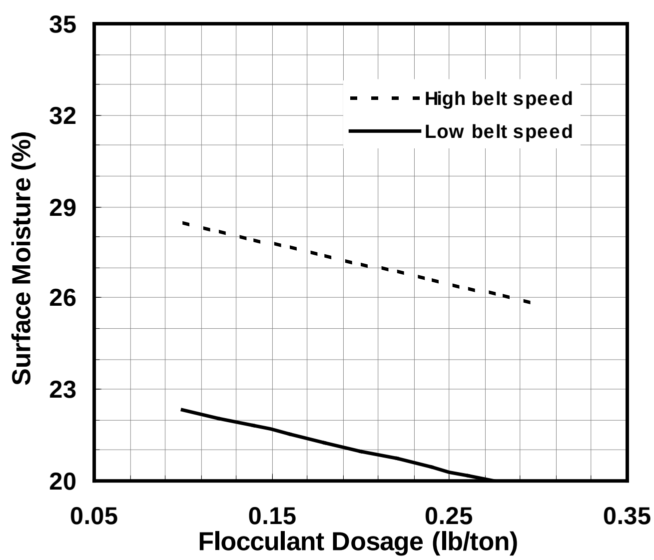


Figure 10: Illustration of the main effects of volumetric feed flow rate and flocculant dosage as well as the effects of feed flow rate-belt speed, feed flow rate-flocculant dosage and flocculant dosage-belt speed interactions on SBF moisture content

Throughput testing: It was desired to maximize the throughput capacity of the prototype unit by increasing feed flow rate as well as feed solid content. The combined spiral and flotation product had a significant amount of 1 mm size coarse particles, which limited the capacity of the feed pump especially at high levels of solids content. A maximum volumetric flow rate of 25 lpm could be fed to the SBF unit at a solid content of nearly 38% in the dewatering feed slurry. At solids content levels higher than 38%, a significant settling of coarse materials in the feed sump was also noticed. Therefore, the solids content of the feed slurry was lowered to 31% at which a maximum of 35 lpm could be fed to the prototype unit without causing any spillage over the edge of the belt. However, this increase in volumetric flow rate was achieved only by increasing the belt speed up to 2.4 m/min, which caused a slight increase in product moisture content. It is believed that the mass throughput to the SBF prototype unit may be further increased by having a pump suitable for coarse coal slurry with high solids content of at least 40%. The mass throughput versus moisture trend illustrated in Figure 11 clearly indicates that higher solids content in the dewatering feed, or in other words, lower liquid content in the feed, results in a lower moisture content product. The lowest product moisture content of 18.5% was observed when a feed slurry with the highest solids content of 38% was used.

It must be realized that the mass throughput values indicated in Figure 11 refer only to dry solid mass. In other words, the maximum dry mass throughput of 0.72 tph actually corresponds to 0.92 tph of dewatered product having moisture content of 21.32%. With respect to the volumetric capacity, a slight increase in product moisture content, i.e., from 20.5% to 21.32%, was observed during this investigation when the volumetric feed flow rate was increased from 18 lpm to 35 lpm at a constant feed solid content of 31%.

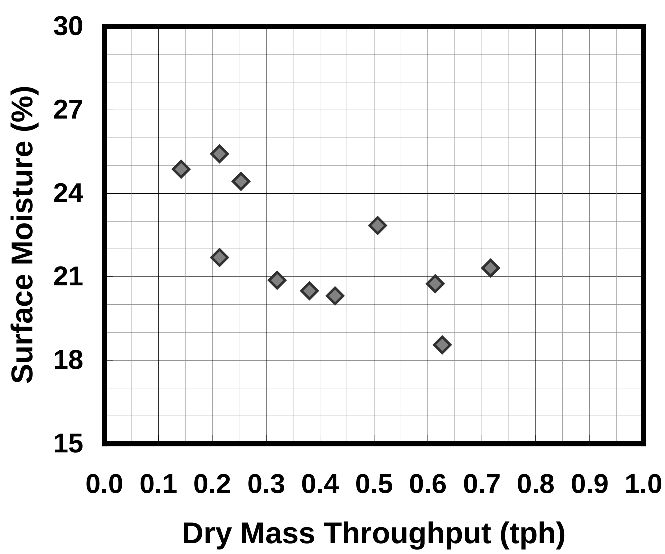


Figure 11: A scatter diagram illustrating the relationship of mass throughput and product moisture content

Evaluation of minus 150 micron flotation product sample: After completing an extensive study using a combination of spiral and flotation products, it was desired to investigate the suitability of the SBF technology for dewatering a froth flotation product. The flotation product was generated using a pilot-scale flotation column at a plant site that treats coal originating from the Illinois No. 6 seam. Predictably, a higher dosage of a flocculant was required to achieve the target solid recovery of nearly 99%. A minimum of 0.6 lb/ton of the anionic flocculant, TX 12417, was required to prevent any significant solid loss to the effluent streams. However, as indicated in Figure 12, increasing flocculant dosage increased the moisture content of the dewatered product. It is believed that larger dosages of flocculant results in a stronger bond among the small particles that form floccs. A stronger inter-particle bond negatively affects the drainage of water from the floccs and thus results in higher moisture content in the product. The additional use of a cationic flocculant (TX 12437) helped lower the product moisture content by an average of 2% as shown in Figure 12. However, the lowest surface moisture content that was achieved while dewatering the flotation only product material was nearly 30%, which was significantly higher than the lowest moisture content achieved with the combined spiral+flotation product. By using a higher dosage of flocculants, solid recovery was maintained above 99%. While conducting the dewatering tests with the flotation only product, the high-quality flocculation action, which was observed with other samples, was not noticed. This may have resulted due to an apparent interaction of the frother and fuel-oil ingrained previously in the flotation product with the flocculant used during the dewatering tests. This phenomenon may have resulted in relatively high product moisture content for the flotation only product. The maximum volumetric flow rate of the flotation only product that could be treated by the SBF prototype unit was only 15 lpm. A significant amount of feed slurry spillage over the side-edge of the belt was noticed at higher feed rates in spite of increasing the flocculant dosage up to 2.0 lb/ton.

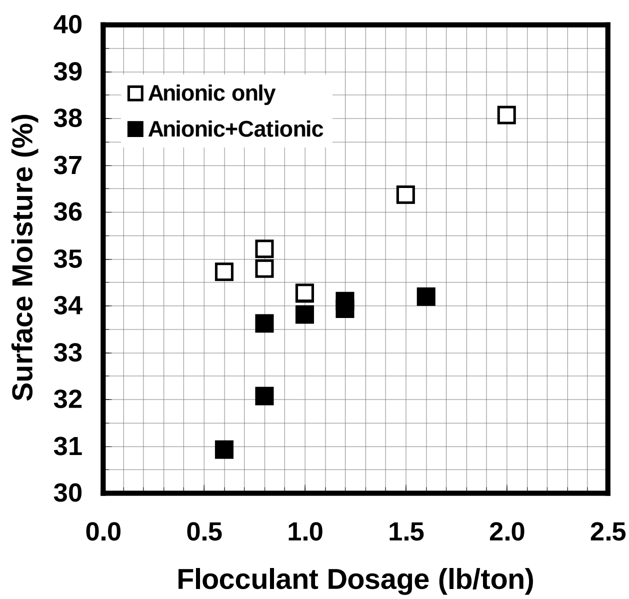


Figure 12: The product moisture contents obtained from the SBF dewatering of a nominally minus 150 micron froth flotation product

Task 4: Evaluation of the SBF technology for Dewatering Fine Coal Tailings

Upon the successful completion of the SBF testing of clean coal dewatering, two fine tailings samples were tested as a part of this research task. As indicated in Tables 4 and 5, a solid recovery of greater than 99% was achieved in both cases. As shown, both high molecular weight anionic polymer (TX 12436) and medium molecular weight polymer (TX 12417) performed equally well for the spiral tailings generated from a Murphysboro seam coal. A direct comparison can be made based on the results of Test 5 and 6 listed in Table 4. A minimum surface moisture content of nearly 18% was obtained at a maximum feed flow rate of 21 lpm and a feed solid content of 21%. The required anionic and cationic dosages were 0.6 lb/ton and 0.3 lb/ton, respectively, which were the same as the flotation product dewatering.

For the extremely fine and high ash thickener underflow tailings collected from a plant treating Illinois No. 5 seam, both high and medium molecular weight polymers performed well. However, to obtain a high recovery of solids the respective dosages for the anionic and the cationic flocculants were raised to 1.6 lb/ton and 0.8 lb/ton. The lowest moisture content of nearly 23% was achieved in the SBF product while recovering more than 99% of the solid materials. A maximum of 20 lpm of feed slurry having a solid content of 20% was dewatered by the SBF unit to produce a moisture content of nearly 28%, which may be considered low for such fine tailings materials having a mean size of 10 micron and an ash content of more than 60%.

Task 5: Economic analysis

Upon completion of the technical evaluation of the SBF prototype, a preliminary economic analysis was conducted to estimate the SBF dewatering cost on a per ton of clean coal basis. This economic analysis has been made for a full-scale SBF unit in consultation with the parent equipment company, Particle Separation System of South Africa. The relevant cost information collected is as follows:

Capital Cost of the unit:		$ 200,000
Annual Operating Cost includes the followings		
Belt replacement:	$10,000	
Re-rubbering of rollers:	$ 2,000	
Bearings:	$ 1,000	
Flocculants:	$28,000	
Electric power and compressed air:	$ 4,000	
Total Annual Operating cost:	$45,000	

By discounting the capital cost of $200,000 at a rate of 12% over a period of 15 years, the annualized capital cost was found to be $29,360. Thus, the total annual dewatering cost was found to be $74,360 (summation of capital and operating cost). Considering 4,000 work-hours/year and 20 tph of throughput capacity for a full-scale SBF unit, dewatering costs were found to be $0.93 per ton of dewatered coal product. Flocculant cost, which is

Table 4: SBF performance obtained from dewatering a spiral tailings material

Test #	Operating Parameters							Results						
	Feed Flow		Belt Speed	Lift Pressure	Chemcials Used (lb/ton)			Vacuum Effluent		Pressure Effluent		Solid	Product Moisture(%)	
	(lpm)	(% solid)	(m/min)	(bar)	Cationic	Anionic	Others	(lpm)	(% solid)	(lpm)	(% solid)	Recovery (%)	Total	Surface
1	8	18	0.7	6	0.3	0.6		4.92	0.03	1.08	0.04	99.89	29.38	21.38
2	8	18	0.7	6	0.4	0.8		5.40	0.01	1.28	0.03	99.93	30.63	22.63
3	8	18	0.7	6	0.5	1.0		5.10	0.01	1.20	0.04	99.93	30.51	22.51
4	8	18	0.7	6	0.6	1.2		5.70	0.01	1.28	0.03	99.93	30.79	22.79
5	10	18	0.7	6	0.4	0.8		6.30	0.01	1.48	0.03	99.95	29.90	21.90
6	10	18	0.7	6	0.4	0.8		5.70	0.01	1.80	0.02	99.95	29.91	21.91
7	10	18	0.7	6	0.3	0.6		6.90	0.01	1.52	0.03	99.95	30.85	22.85
8	12	18	0.7	6	0.3	0.6		7.20	0.01	1.72	0.02	99.95	29.04	21.04
9	12	18	0.7	6	0.4	0.8		6.90	0.01	1.72	0.07	99.92	28.15	20.15
10	15	18	0.7	6	0.3	0.6		7.50	0.01	2.00	0.07	99.93	27.64	19.64
11	15	18	0.7	6	0.4	0.8		8.10	0.01	1.60	0.03	99.96	28.27	20.27
12	15	21	0.7	6	0.3	0.6		6.90	0.17	2.60	0.14	99.56	25.78	17.78
13	15	21	0.7	6	0.4	0.8		6.60	0.16	2.28	0.26	99.53	27.76	19.76
14	18	21	0.7	6	0.3	0.6		6.30	0.09	3.32	0.15	99.75	27.03	19.03
15	21	21	0.7	6	0.3	0.6		11.70	0.02	4.80	0.35	99.62	26.33	18.33
16	21	21	0.7	6	0.3	0.6		14.40	0.02	3.30	0.46	99.64	31.02	23.02
17	18	21	0.7	6	0.3	0.6		9.00	0.06	3.78	0.22	99.67	26.02	18.02
18	18	21	0.7	6	0.3	0.6		9.30	0.06	4.20	0.83	99.01	32.77	24.77

Test s1-5; chemicals used were TX12417 (Anionic) +TX12437 (Cationic); Tests 6-18; TX12436 (Anionic) + TX12437 (Cationic)

Table 5: SBF performance obtained from dewatering thickener underflow tailings material

Test #	Operating Parameters							Results						
	Feed Flow		Belt Speed	Lift Pressure	Chemcials Used (lb/ton)			Vacuum Effluent		Pressure Effluent		Solid	Product Moisture(%)	
	(lpm)	(% solid)	(m/min)	(bar)	Cationic	Anionic	Others	(lpm)	(% solid)	(lpm)	(% solid)	Recovery (%)	Total	Surface
1	8	20	0.7	6	0.5	1.0		2.92	0.46	2.20	7.46	89.99	35.44	23.44
2	8	20	0.7	6	0.8	1.6		3.44	0.08	1.88	0.23	99.59	37.88	25.88
3	12	20	0.7	6	0.8	1.6		2.70	0.13	2.70	0.17	99.70	33.62	27.63
4	15	20	0.7	6	0.8	1.6		5.70	0.01	5.70	0.07	99.86	38.60	26.60
5	12	20	0.7	6	0.8	1.6		3.30	0.06	3.30	0.17	99.72	39.63	23.12
6	12	20	0.7	6	0.5	1.0		3.32	0.21	3.32	1.13	98.34	37.18	25.18
7	15	20	0.7	6	0.8	1.6		4.20	0.09	4.40	0.09	99.77	41.28	29.28
8	20	20	0.7	6	0.8	1.6		6.60	0.10	5.70	1.14	98.35	40.04	28.04
9	20	20	0.7	6	0.8	1.6		6.90	0.09	6.00	0.53	99.12	40.15	28.15

Tesst 1-3; chemicals used were TX12417 (Anionic) +TX12437 (Cationic); Tests 4-9; TX12436 (Anionic) + TX12437 (Cationic) a major portion of the operating cost, was calculated based on 0.2 lb/ton of anionic and 0.1 lb/ton of cationic flocculant.

Task 6: Report Preparation

This project started on September 1, 2002 and continued until October 31, 2003. During this period, 13 monthly progress reports were submitted in a timely manner. This is the final technical report being submitted to the Illinois Clean Coal Institute.

CONLCUSIONS AND RECOMMENDATIONS

More than 120 dewatering experiments were conducted over a period of 14 months as a part of this research project using the newly developed Steel Belt Filter (SBF) technology for the first time in the US. The SBF prototype unit used in this investigation conducted at the Illinois Coal Development Park had a belt width of 0.6 meter and a maximum product throughput capacity of nearly one tph. The major conclusions and recommendations of this comprehensive experimental investigation and economic analysis are listed in the following sections:

Conclusions

- The unique use of pressure and vacuum simultaneously in the SBF technology has enabled the process to effectively dewater both fine clean coal and fine tailings materials. The four coal samples used in this investigation were collected from three different coal preparation plants which treat coal originating from Illinois No. 5, Illinois No. 6 and Murphysboro seams. The mean particle sizes of the clean coal and tailings samples were 400 micron, 50 micron, 20 micron and 10 micron, respectively; whereas the ash contents were 19.2%, 6.2%, 36% and nearly 60%, respectively.

- The dewatering results obtained from the optimization test program, which was conducted using the coarsest sample (combination spiral+flotation product), indicates that the solid recovery changed only marginally from 98.5% to 99.9% over the entire test program. However, the surface moisture content, which was determined by subtracting the inherent moisture content of the given coal from the total moisture content analysis of the test samples, was found to be most sensitive to the fluctuation in feed solid content and the flocculant dosage. The surface moisture content decreased by nearly 6% with an increase in the feed solids content from 18% to 36%. Similarly, a moisture reduction of nearly 3% was noticed with an increase in flocculant dosages from 0.1 lb/ton to 0.3 lb/ton. The effects of other process parameters, such as belt speed and volumetric flow rate were statistically significant; however of lesser magnitudes.

- The lowest surface moisture levels achieved during this investigation were 18.5%, 31%, 18% and 23% for the combination spiral+flotation product, flotation product only, spiral tailings and thickener underflow tailings samples, respectively. It is noteworthy that these excellent moisture contents were achieved while maintaining solid recovery levels above 99% for each sample. The relatively high moisture content achieved with the flotation product sample may be partly due to a possible interaction of the flocculants used with the frother and fuel oil that was already ingrained in the flotation product sample. The high-quality flocculation action, which was observed with other samples, was not noticed with the dewatering of the flotation sample despite trying a variety of flocculants in consultation with the ONDEO Nalco Company personnel.

- The maximum product throughput that was achieved with the SBF prototype during this investigation was 0.92 tph (as received basis), while maintaining a surface moisture content of nearly 21%. This was achieved by treating 35 lpm (nearly 9 gpm) of a combined flotation+spiral product having a solid content of 31%. The sump and pump assembly that was used in this investigation restricted the use of higher mass flow rates. Based on visual observation, it appeared that the product throughput may be marginally improved by having a better sump and pump arrangement.

- Based on a preliminary economic analysis conducted using the cost information provided by the parent equipment company, Particle Separation Systems of South Africa, as well as the technical data generated during this investigation, it is estimated that fine coal dewatering of the combined spiral+flotation product using a full-scale SBF unit may cost $0.93/ton of coal product. The same dewatering cost may be applicable for the spiral tailings; however, the cost for dewatering flotation only product and thickener underflow tailings material using the SBF technology may be slightly higher.

- Most of the research objectives of this investigation were achieved or in many cases surpassed with the exception of achieving a surface moisture content of less than 20% for the flotation product. However, the apparent reason for this discrepancy has been previously explained.

<u>Recommendations</u>

- The spray bar for the upper belt of the SBF unit may be moved to the feed side from its present location at the product side. This should obviate the need for a suction bar on the upper belt to catch the excess water that trickles down to the product discharge end and increases the moisture content of the dewatered product.

- With the existing design of the unit, the dewatering feed slurry is subjected to a suction (vacuum) force immediately after being introduced on the steel belt and the formation of filter cake starts. After a few seconds of being subjected to vacuum, the cake passes through the mechanical squeeze (pressure) section between the upper and lower belt, which is equipped with 8 rollers. From visual observations, it was clear that the entire pressure effluent was squeezed out at the first four rollers; no more effluent was generated at the last four rollers. Based on this observation, it is recommended that the mechanical squeeze section of the SBF unit be shortened by almost 50%. In addition, it is recommended that the suction force be applied throughout the belt length instead of just the first half of the belt. This design modification may enable the SBF technology to achieve even lower product moisture levels with a significantly smaller foot-print area.

- As discussed in the conclusion section, higher product throughput may be achievable from the SBF prototype unit tested during this investigation by using a more suitable pump and sump assembly. Further study is recommended in this area.

- Based on this successful evaluation of the pilot-scale SBF technology at the Illinois Coal Development Park, an on-site evaluation of the SBF technology is strongly recommended for its near-term commercialization in the coal industry in Illinois.

AKNOWLEDGEMENT

The Principal Investigator greatly appreciates the dedicated effort of his SBF research team, which includes Mr. Zhigang Wang, Mr. Richard Geilhausen and Mr. Derek Liunius for the successful completion of this research project. Special thanks are due for Mr. Amit Patwardhan and Dr. Paul Chugh for their assistance with the collection of samples from multiple plant sites. The project cooperation received from a variety of agencies including Mr. Rein Buisman of the PSS (South Africa), Mr. Kobus Reyneke of the Waltech group, Dr. Sankar Bhattacharya and Mr. Ken McGough of ONDEO Nalco, Mr. Steve Carter from Knight Hawk Coal, and plant personnel from White County Coal and Turris Coal are also greatly appreciated. Last but not least, the research funds from the ICCI/DCEO and the cooperation of the Coal Research Center at SIU are sincerely acknowledged. Without their support this project would not have been feasible.

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