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**DEVELOPMENT AND DEMONSTRATION OF INTEGRATED CARBON
RECOVERY SYSTEMS FROM FINE COAL PROCESSING WASTE**

(Draft Final Report: January 1, 1999-July 15, 2000)

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Project Manager: Mr. Carl Maronde
Project Contract No.: DE-AC26-98FT40152

VOLUME I

ACQUISITION & ASSISTANCE
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VOLUME I

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Chapter 1	Introduction and Overall Research Program
Chapter 2	Sample Acquisition and Characterization
Chapter 3	Hydraulic Gravity and Classification Separations
Chapter 4	Enhanced Gravity Concentration
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Chapter 1

Introduction and Overall Research Program

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July 2000

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INTRODUCTION AND PROBLEM STATEMENT

Energy independence has been a goal of the United States for several decades, during which time the largest energy resource has been coal. As a result of this goal and the relatively low cost for coal, the proportion of electricity production generated from coal has risen to 54% in 1996 and, likewise, the overall annual production of coal has increased to record levels in excess of 1 billion tons. During this same period, the ability to efficiently treat the -28 mesh material in the processing plant, which typically represents 10% - 20% of the run-of-mine feed, has been limited due to the lack of effective technologies and the inability to dewater the final product to acceptable levels. Thus, vast quantities of fine, high quality carbon material have been disposed into fine-coal refuse ponds for several decades, thereby representing not only a loss of valuable energy resources but also the creation of an environmental hazard.

Since the increased mechanization of underground coal mining, the proportion of fine coal (i.e., -28 mesh) reporting to the coal processing plants have increased from as low as 5% to as high as 20% of the overall run-of-mine production. Current trends in the coal industry indicate the desire to increase the top particle size reporting to the fine circuit to about 10 mesh in order to reduce the load on the intermediate circuits or to allow processing of the entire +10 mesh fraction using a single unit operation. Obviously, this trend will ultimately result in greater amounts reporting to the fine circuit, which have traditionally used relatively inefficient technologies for recovering the carbonaceous material. In fact, some coal processing plant operators have opted for disposal of the fine material due to the lack of technologies available for treating moderately difficult-to-clean fine coal and for dewatering of the final product. The result of these practices is an abundance of fine-coal refuse ponds that contain a significant amount of carbon material, for which, a high purity could be obtained after cleaning. In addition, due to the presence of fine coal pyrite, the refuse ponds generated from high-sulfur coal have high potential for acid generation.

The difficulty in recovering the carbon from fine-coal refuse ponds is dependent upon the cleaning scheme of the coal processing plant supplying the refuse material and the inherent characteristics of the run-of-mine coal. In fact, the origin of the feed coal to a processing plant could change several times during the life of a preparation plant, which adds complexity to the nature of the refuse ponds. In addition, wide variations in quality can be commonly traced to the history of the discharge position of the plant tailings stream. Thus, processes that can effectively handle wide variations in feed characteristics and provide efficient carbon recovery are required to obtain universal success in the processing of fine-coal refuse ponds.

To date, the most common strategy used to recover the carbon from fine-coal refuse ponds incorporate the use of spiral concentrators to treat the nominal +100 mesh material and column flotation cells to clean the -100 mesh size fraction. However, some of the problems that need to be addressed prior to considering an application at a given refuse pond site, i.e.,

- a) Spiral concentrators have a relatively low mass throughput capacity of 3 to 3.5 tons/hour per start. To treat a typical mass flow of 120 tons/hour, a total of 40 starts may be needed. Thus, an efficient distribution system is required that provides equal quantities of both mass and volume to each of the starts to maintain an efficient separation performance.
- b) Spiral concentrators typically have high separation densities (<1.80) and average separation performances as indicated by probable error (E_p) values between 0.12 and 0.18. Due to these reasons, it is difficult to achieve low product ash contents when treating moderately difficult-to-clean coals. Realizing this problem, several researchers have made efforts to develop circuitry arrangements of spirals for lowering the separation densities (1.60 – 1.80) and producing acceptable product qualities. Luttrell et al. (1999) conducted an excellent study on this subject and demonstrated a spiral circuitry that could produce lower separation densities of about 1.60 in an operating preparation plant. Toney et al. (1998) also arrived at similar conclusions from tests at a different coal cleaning plant. However, the E_p values for the overall circuit increased to over 0.18, which indicates a reduction in efficiency.
- c) Classification of the feed material to achieve the 100-mesh particle size cut is generally realized using a hydrocyclone. The underflow stream of the cyclone reports to the spirals while the overflow stream reports to froth flotation. Hydrocyclones inherently by-pass about 25% – 30% of the ultrafine material to the underflow stream which is screened out of the spiral product. If the screen underflow contains significant amounts of coal pyrite, it is generally desirable to reject the stream to tailings, thus causing a significant coal loss.
- d) It is typical for coal refuse ponds to contain widely varying particle size distributions at different locations throughout the area of the pond. Some parts of the coal refuse pond contain large proportions of fine (-100 mesh material) compared to others. This causes problems in the flotation system due to carrying-capacity constraints and the required adjustments in the operating conditions and chemical dosages.
- e) Despite the production of a high quality carbon product, difficulties in dewatering may deter the marketability of the end product. Current dewatering technologies provide moisture reductions to about 20% for minus 28 mesh carbon whereas the moisture reduction for -100 mesh material is typically around 25% to 30% moisture. Hence, it is essential to develop an enhanced dewatering technology to market the product.
- f) One of the most problematic areas for coal mining has been the generation of acid drainage around the refuse ponds, which contaminate both the surface and ground water. The secondary mining of refuse ponds to recover the carbon will increase the acid generating potential of the refuse material due to exposure of the acid producing components to air. Thus, an effective carbon recovery system requires environmental remediation in order to realize a successful operation.

The integrated system presented in this study will eliminate or significantly reduce the impacts of the problems stated above.

GOALS AND SPECIFIC OBJECTIVES

The project involves the development of an efficient, environmentally friendly system for the economical recovery of carbon from fine-coal refuse ponds. The project will be conducted in two phases. Phase I was involved the development and evaluation of process equipment and techniques to be used in carbon recovery, product dewatering and reconstitution, and refuse management. Phase II will integrate the various units into a continuously operating circuit that will be demonstrated at a site selected based on the results presented in this study.

The project focused on the treatment of high sulfur fine coal refuse ponds, specifically since these sources provide the ultimate challenge in terms of environmental remediation and cleaning to acceptable carbon qualities. To achieve this goal, two processing schemes utilizing state-of-the-art fine particle processing technologies were evaluated. The first scheme utilized a heavy media application to an enhanced gravity concentrator commercially known as the Falcon Concentrator and a novel froth flotation system incorporating the Jameson Cell technology and the ISGS Froth Washer. The second process flow sheet represented a water-only circuit that may prove to be desirable for the treatment of waste in which the carbon is easy to recover at the desirable grade. The water-only circuit involved the use of a novel hindered-bed concentrator that has been recently designed by Eriez Magentics to apply air assistance to recover the coarse carbon particles. After the initial rejection of coarse ash-bearing material by the Eriez separator, the clean coarse carbon (16 x 48 mesh) was recovered from the overflow of a screen while enhanced gravity concentration and froth flotation were applied to clean and recover the fine carbon.

Despite the production of a high quality carbon product, difficulties in dewatering may deter the marketability of the end product. Current dewatering technologies provide moisture reductions to about 20% for minus 28 mesh carbon whereas the moisture reduction for -100 mesh material is typically around 25% to 30% moisture. Thus, to ensure a market for the high quality carbon, new dewatering techniques were developed. The researchers at the Center for Applied Energy Research (CAER)/University of Kentucky have led the research efforts in this field and investigated innovative concepts in this study. A redesign of a hybrid vacuum/pressure filter was evaluated in conjunction with and without additives, such as coarse clean coal to increase the cake capillary size. In addition, a modification of the Granuflow process was studied in an effort to economically reconstitute the fine carbon particles into a more easily handled product.

One of the most problematic areas for coal mining has been the generation of acid drainage around the refuse ponds, which contaminate both the surface and ground water. The secondary mining of refuse ponds to recover the carbon will increase the acid generating potential of the refuse material due to exposure of the acid producing

components to air. Thus, an effective carbon recovery system requires environmental remediation in order to realize a successful operation. The concept of concentrating the acid-producing components using an enhanced-gravity concentrator followed by subsequent remediation techniques was investigated. An innovative approach of refuse management developed at Southern Illinois University-Carbondale (SIUC) was investigated. This approach employs the use of coal combustion residues to neutralize the harmful environmental effects of acid-producing components such as coal pyrite.

The following project objectives have been realized in Phase I:

1. Feasibility evaluation of the ability of the enhanced-gravity concentrator to handle a wide range of feed characteristics (i.e., particle size, ash and sulfur contents, etc.). The efficiencies of the water-only and dense-medium enhanced gravity applications were evaluated over a range of feed characteristics.
2. Development of an automation and control system for the enhanced-gravity system in order to handle the variable feed characteristics.
3. Development of an efficient magnetite recovery system for the dense-medium application of the Falcon Concentrator.
4. Development and testing of a novel flotation system incorporating the Jameson Cell technology and the ISGS Froth Washer.
5. Performance of a technical and economical comparison of the dense-medium circuit and water-only systems performed on the two refuse pond samples.
6. Evaluation of hybrid filtration systems and the effects of additives such as coarse coal particles on the dewatering of fine carbon particles.
7. Development of a new application of the GranuFlow process for the reconstitution of the product to ensure effective handling and transportation.
8. Evaluation and assessment of the environmental benefits from the treatment of the tailing streams generated from the circuits using innovative refuse management techniques and potential concentration of the acid producing components.

The results show that the recovery of carbon in abandoned and active refuse ponds may prove highly efficient and profitable. The system developed is adaptable to the processing of most coal refuse pond materials. In addition, during the process of recovering the carbon, acid generating material that causes ground water contamination was made benign and non-hazardous to the environment through the use of the residual material of coal combustion. Therefore, the integration of the units evaluated in this study resulted in a unique system that will provide positive economical and environmental impacts on society.

OVERALL APPROACH

Toward the above goals, Southern Illinois University at Carbondale (SIUC) successfully coordinated and developed a research and development program with the following participating researchers and organizations.

1. Dr. B. K. Parekh, Center for Applied Energy Research, University of Kentucky,
2. Dr. Latif Khan, Illinois State Geological Survey,
3. Dr. R. Q. Honaker, Department of Mining Engineering, University of Kentucky

Subdivision of the Overall Research Program

The proposed program was divided into 5 areas for the purpose organizational structure as well as for the technical planning under the overall technical direction of the Principal Investigator (PI). These broad areas are:

- 1) Enhanced Gravity Separation,
- 2) Advanced Flotation
- 3) Circuit Optimization
- 4) Enhanced-dewatering
- 5) Refuse Management.

Enhanced Gravity Separation

This group was responsible for the following:

- 1) Characterization of refuse pond material and preparation of samples for co-investigators
- 2) Design and optimization studies on the dense-medium and water-only Falcon concentrator
- 3) Process control and automation of the Falcon concentrator.

This group was led by Dr. R. Q. Honaker, as Associate Professor, and Dr. D. P. Patil, Mr. Amit Patwardhan, Dr. A. A. Sirkeci and Dr. J. P. Barnwal, all researchers in the Department of Mining and Mineral Resources Engineering.

Advanced Flotation

This group was responsible for the following:

- 1) Design and optimization studies with column flotation with and without ISGS washer
- 2) Design and optimization studies with modified Jameson cell design incorporating a ISGS washer.

This group was led by Dr. L. Khan of ISGS as a co-PI and Ms. D. D. Patil as a researcher. Dr. R. Q. Honaker and Mr. Amit Patwardhan participated in the task activities from Southern Illinois University.

Circuit Optimization

This group was responsible for the following:

- 1) Studies on hydraulic classification
- 2) Evaluation of media recovery circuit
- 3) Circuit simulation and optimization.

Dr. R. Q. Honaker provided leadership for this task from the University of Kentucky.

Enhanced Dewatering

This group was responsible for:

- 1) Hybrid vacuum/pressure dewatering with improved filter design
- 2) Effect of size distribution on enhanced dewatering
- 3) The Granuflo process
- 4) Effect of additives
- 5) Handleability study of the dewatered product.

Dr. B. K. Parekh of CAER led this group, along with Dr. Tao and Dr. Z. Chen from the University of Kentucky.

Tailings Management

This group was responsible for:

- 1) Characterization of FCPW Pond Feed, tailing streams and CCBs
- 2) Identify Sources of CCBs for Co-Management and Characteristics of Mixes
- 3) Mix Development and its Characterization
- 4) Small-Scale Laboratory Demonstration and Preliminary Economic Analysis.

Dr. Y. P. Chugh, Professor and Chair, Department of mining Engineering, SIUC, led this group, with Dr. C. B. Raju as a researcher.

REPORT ORGANIZATION

This report has been sub-divided into chapters corresponding to five main subdivisions listed above to facilitate overall report preparation effort. The chapters prepared by group coordinators were integrated to develop this synthesized report. A summary of the report is included in Chapter 12. Each chapter has tables of content, figures and tables. Pages are numbered consecutively within each chapter. References and appendices are included at the end of each chapter. The report consists of a total of 12 chapters. The chapters and the organizations preparing the chapters are:

Chapter 1	Introduction and Overall Research Program	SIUC
Chapter 2	Sample Acquisition and Characterization	SIUC
Chapter 3	Hydraulic Gravity and Classification Separations	UK
Chapter 4	Enhanced Gravity Concentration	SIUC
Chapter 5	Magnetite Recovery Systems	UK
Chapter 6	Froth Flotation	ISGS
Chapter 7	Circuit Simulation and Optimization	UK
Chapter 8	Processing Studies Synthesis and Overview	SIUC
Chapter 9	Dewatering and Handleability	CAER
Chapter 10	Tailings Management	SIUC
Chapter 11	Engineering Economic Evaluation	SIUC
Chapter 12	Summary and Conclusions	SIUC

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Chapter 2

Sample Acquisition and Characterization

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July 2000

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SUMMARY OF WORK

Development and Demonstration of Integrated Carbon Recovery Systems from Fine Coal Processing Waste

(Summary of work completed as part of Phase I Project)

Task 1 – Sample Acquisition and Characterization

Tasks Proposed

Task 1 Acquisition and Characterization of Fine Coal Slurry Samples

All items included in the original proposal were addressed. FCPW samples from two locations, one in Illinois and another in West Virginia were collected.

Task 1.1 Sample Collection

All items included in the original proposal were addressed. The Illinois No. 6 seam FCPW pond was randomly sampled before choosing a location for collection of sample. Location for the Pittsburgh No. 8 seam FCPW pond was chosen from available pond borehole data.

Task 1.2 Sample Preparation

All items included in the original proposal were addressed.

Task 1.3 Representative Sampling

All items included in the original proposal were addressed. Sample was carefully split into representative lots. Individual lots were sampled and analyzed to determine the statistical variability between the lots.

Task 1.4 Sample Characterization

All items included in the original proposal were addressed.

Task 1.5 Washability Tests

This task was satisfactorily concluded.

Task 1.6 Release Analysis Tests

This task was satisfactorily concluded.

Task 1.7 Sample Processing and Distribution

This task was satisfactorily concluded.

Additional Tasks Accomplished

1. The Illinois No. 6 seam FCPW sample was found to have poor floatability. Thus, a size-by-size release analysis tests were conducted to identify the source of the problem.
2. In addition to release analysis on the -65 mesh and -325 mesh size fractions, release analysis tests were conducted on the -48 mesh size fractions of both the FCPW samples.

ABSTRACT

Samples from two different refuse coal ponds were collected for use in this investigation. The refuse pond sites include the Humphrey Mine of CONSOL Inc. in northern West Virginia and Peabody's Randolph Mine located in Marissa, Illinois. The fine coal refuse from the Humphrey site was derived from the Pittsburgh No. 8 coal seam whereas the Randolph pond represents Illinois No. 6 seam coal. The specific sampling locations from within each pond were determined using existing borehole information for the Humphrey pond and random sampling characterization data for the Randolph pond.

Characterization of the Pittsburgh No. 8 fine coal refuse revealed that only about 2.6% of the total weight has a particle size greater than 16 mesh whereas 29.5% is less than 500 mesh. The ash and total sulfur contents of the sample are 31.63% and 4.73%, respectively, with an ash content of the -500-mesh size fraction being 50.7%. The calorific value of the head sample was found to be around 10,000 BTU/lb on a dry basis. According to washability results, the Pittsburgh No. 8 refuse material is considered to be moderately difficult-to-clean using gravity-based processes based on a 5% - 10% content of near-gravity material. The data suggest the possibility of producing a product containing 9% ash while recovering greater than 90% of the combustible material. Result from release analysis tests, which were conducted on -65 mesh material, indicates that froth flotation has the ability to produce a clean coal concentrate containing 10.7% ash with a combustible recovery of nearly 92%.

Characterization of the Illinois No. 6 fine coal refuse, collected from Peabody's Randolph refuse ponds located near Marissa, Illinois, showed that about 4.4% of the total weight has a particle size greater than 16 mesh while 500 mesh size fraction is less than 36.2%. The ash and total sulfur contents of the sample are 33.11% and 2.21%, respectively, with an ash content of the -500-mesh size fraction being 65.6%. The head sample provides a calorific value of around 8600 BTU/lb on a dry basis. Washability results suggest that, the Illinois No. 6 refuse material is considered to be moderately easy-to-clean using gravity-based processes based on a 5% - 10% content of near-gravity material. The data imply the possibility of obtaining a clean coal product containing 7.5% ash while recovering greater than 95% of the combustibles for +325-mesh size fraction. Results from release analysis tests, conducted on -48, -325 and 48 x 325-mesh materials, indicate that froth flotation is rather ineffective to produce a clean coal concentrate with an adequate level of combustible recovery.

The proposed circuit was operated to produce the required size and quality consist feed material to be used for investigation by the other participating research teams. The hydrofloat studies used the as received FCPW feed. The flotation tests were conducted on the -48 mesh and -325 size fractions of the as-received FCPW material. The dewatering group was provided with the combined circuit product. The tailings management group was provided the combined circuit tailings as well as the pyrite rich fraction generated by retreating the primary Falcon concentrator rejects. In addition, the dewatering and tailings management groups were provided with representative samples of the as received FCPW samples for establishment of baseline benchmarks.

GOALS AND SPECIFIC OBJECTIVES

The first step after initiation of the project was the identification of suitable FCPW pond sites. The aim was to select sites that contained a high amount of pyritic sulfur. A high middlings FCPW was also desired to evaluate the proposed circuit performance while treating a difficult to clean material and to evaluate the benefits of the dense-medium enhanced gravity concentration technology.

- Identification of two FCPW pond sites based on available pond characterization data.
- Sample collection from both the FCPW pond sites.
- Sample preparation and splitting into representative lots for ensuring consistent quality material for future investigations.
- Distribution of unprocessed and processed samples to various participating research teams and DOE.

OVERALL APPROACH

The overall methodology adopted for achieving the goals of this task is shown in Figure 2.1. Two FCPW pond sites were identified after consultation with several coal companies and based upon their willingness to participate in this study. One site was situated in southern Illinois and the other in northern West Virginia. The Illinois site contained the Illinois No. 6 seam FCPW while the West Virginia site contained Pittsburgh No. 8 seam FCPW.

Pittsburgh No. 8 Seam FCPW Site

Borehole sampling data was available for the West Virginia site. Thus, a location in the pond having high pyritic sulfur and middling content was selected. The sample collection was conducted by Consol and the samples were shipped to SIU facilities. Upon receiving the samples, the entire sample was mixed, homogenized and split into representative lots in 55 gallon drums. The representative samples were sent to all the participating team members. The representative sample was treated in the proposed advanced fine coal cleaning (AFCC) circuit. The tailings from the hydrosizer, Falcon concentrator and flotation columns was combined and delivered to the tailings management group. The clean coal product from the hydrosizer clean coal screen, falcon clean coal screen and flotation froth product was reconstituted and shipped to the dewatering group. The tailings from the falcon concentrator were retreated in the Falcon concentrator to generate a very heavy pyrite rich stream. This stream was also provided to the tailings management group. Samples were collected from all points in the circuit to determine the circuit mass yield and product quality. The overall scheme of sample preparation is presented in Figure 2.1.

Illinois No. 6 Seam FCPW Site

Upon initiation of the project, SIUC staff visited Peabody's Marissa mine pond sites and conducted random sampling at various locations in the ponds. The samples were analyzed for ash and sulfur content in the laboratory to select a suitable sample. Upon selection of the sample location, bulk samples were collected from the site and brought back to SIUC. The samples were then mixed, homogenized and treated in a similar fashion as described for the Pittsburgh No. 8 seam sample.

Figure 2.1. Sample Identification, collection, preparation and distribution.

RESULTS AND DISCUSSION

Acquisition and Characterization of Fine Coal Slurry Samples

As described in the Project Management Plan, Task 1 involved the acquisition and characterization of two fine coal refuse pond samples. Due to weather constraints and scheduling difficulties at the mine sites, a delay in sample acquisition was experienced and, thus, the initiation of several project tasks was delayed. The results of the acquisition and characterization of the Pittsburgh No. 8 and Illinois No. 6 refuse pond samples are presented in this report.

Sample Collection

The sample to be used in the experimental work was obtained from refuse ponds located at CONSOL Inc.'s Humphrey mine located in northern West Virginia which extracts coal from the Pittsburgh No. 8 coal seam and Peabody's Randolph mine in Marissa, Illinois which extracts coal from the Illinois No. 6 seam.

The specific location on the Humphrey slurry pond from which the sample was collected was determined existing borehole information. The actual collection of the sample was performed by authorized personnel of CONSOL Inc. The extraction of 20 barrels of material from the refuse pond was achieved using a backhoe. The wet sample was transferred into barrels that were approximately $\frac{3}{4}$ full, sealed and sent to the Illinois Coal Development Park located in Carterville, Illinois.

The specific location on the Peabody's Randolph mine slurry pond from which the sample was collected was determined using random sampling of the pond. The sampling was achieved by boring a 4-inch diameter hole at a depth of five feet and capturing the contents. The samples were analyzed for ash and total sulfur contents as well as subjected to a particle size-by-size analysis. SIUC researchers and authorized personnel of the Peabody's Randolph mine performed the collection of the sample. The extraction of 40 barrels of material from the refuse pond from the selected site was achieved using a backhoe. The moist sample was transferred into barrels, sealed and sent to the Illinois Coal Development Park located in Carterville, Illinois.

Sample Preparation

Sample preparation is one of the most important tasks in mineral processing and should be performed elaborately. Samples to be used throughout the experimental work should sustain their chemical and physical characteristics to maintain accuracy and consistency. Therefore, great care should be taken during the sample preparation stage. Since the original sample was collected from the different locations of the refuse pond and directly stored in the barrels, sample preparation was required to obtain homogeneously mixed samples.

Based on discussions held between the principle investigator and DOE representatives, sample preparation was accomplished by mixing the material into a slurry state by the addition of water and then by splitting it into empty barrels. For this purpose, a large 2000-gallon mixing tank was employed along with a 5-hp pump to extract the slurry through an underflow discharge point. To ensure representative splitting of the sample, the pump discharge was cycled around the barrels, which were protected with a liner, using an equal time interval for each barrel. Furthermore, the sequence of the barrels was maintained constant throughout the sample splitting. Consequently 18 barrels of Pittsburgh No. 8 and 41 barrels of Illinois No. 6 refuse pond samples were obtained.

Of the total, 8 barrels of Pittsburgh No. 8 and 29 barrels of Illinois No. 6 refuse pond samples were sent to the Federal Energy Technology Center in Pittsburgh while the

remaining barrels were kept in Illinois Coal Development Center to be used in the project.

Representative Sampling

To characterize the physical and chemical properties of the individual barrels and eventually the whole material, representative samples were drawn from each barrel. To achieve effective barrel sampling, a 2-in diameter PVC pipe was employed that was enclosed on one end with an outlet valve. With the valve open, the non-restricted end of the pipe was inserted into the barrel at a random point. The valve was then closed and the pipe was withdrawn with the contents intact due to the resulting vacuum. This procedure was repeated on different parts of the barrel until eventually about 3 to 4 gallons of sample was collected from each barrel into a bucket.

The bucket sample obtained from each barrel was further reduced using a rotary slurry splitter, which produces two equal sample splits of 2 liters each. The representative samples obtained from the slurry splitter were used to verify an equal split of sample in each barrel and for all the sample characterization including gravity washability and release analysis tests. The remaining sample from the rotary splitter was returned to the respective barrel of origin.

Sample Characterization

Representative samples obtained from each barrel were analyzed for ash and total sulfur contents. Ash analyses were performed using the standard ASTM specified method. In this method, ash is determined by weighing the residue after burning the coal under rigidly controlled conditions of sample weight, temperature, time, atmosphere and equipment specifications. For sulfur analyses, a LECO SC-32 Model 780-600 model sulfur analyzer was utilized. The reference samples used were LECO series 501 bituminous coal samples which have been standardized in accordance with ASTM D-3177 Eschka methodology.

The results shown in Tables 2.1 and 2.2 regarding the analyses of the samples from each of the barrels containing Pittsburgh No. 8 and Illinois No 6 fine-coal refuse suggest that both ash and total sulfur contents have acceptable variations. Therefore, all barrels were assured to possess similar properties and hence a representative bulk sample was prepared by combining the same amount of material from each barrel. The composite sample was subjected to particle size analysis using the wet sieving technique. The material collected in each particle size fraction was subsequently analyzed for ash, total sulfur, pyritic sulfur and calorific value contents. For the calorific value determination, a LECO AC-350 Model BTU analyzer was used. The reference samples used were the LECO Series 501 bituminous coal samples, which have been standardized in accordance with ASTM D-3286 isoperibol calorimetry. The results are presented in Tables 2.3 and 2.4.

Table 2.1. The results of ash and total sulfur analyses of the representative samples obtained from each of the 18 barrels containing the Pittsburgh No. 8 fine coal refuse material.

Sample No	Ash	Total Sulfur
C1	31.43	4.66
C2	31.74	4.57
C3	30.68	4.65
C4	31.13	4.73
C5	30.30	4.45
C6	31.03	4.54
C7	31.92	4.63
C8	32.02	4.74
C9	31.23	4.71
C10	31.45	5.35
C11	31.50	4.90
C12	32.21	4.32
C13	32.51	4.62
C14	32.23	4.85
C15	32.40	4.61
C16	31.85	5.01
C17	31.85	4.80
C18	31.87	5.02
Average	31.63	4.73
Std. Deviation	0.59	0.24
95% conf. level	0.30	0.12

Table 2.2. The results of ash and total sulfur analyses of the representative samples obtained from each barrel containing the Illinois No. 6 fine coal refuse material.

Drum No	Ash (%)	Total Sulfur (%)
1	33.38	2.35
2	32.37	2.04
3	32.50	2.39
4	33.15	2.25
5	33.64	2.23
6	32.78	2.47
7	33.07	2.39
8	31.21	2.43
9	32.65	2.52
10	34.90	2.21
11	34.65	2.26
12	33.76	2.32
13	32.34	1.97
14	33.03	2.31
15	33.91	2.40
16	32.90	2.20
17	33.00	2.36
18	32.48	2.36
19	33.40	1.86
20	33.16	2.29
21	33.40	2.50
22	31.79	2.57
23	32.61	2.30
24	33.86	2.55
25	32.68	2.24
26	32.48	2.06
27	33.08	2.38
28	31.70	2.39
29	33.46	2.08
Mean	33.01	2.30
Std. Dev.	0.8	0.17
95% Confidence Level	0.31	0.07

Table 2.3. The physical and chemical properties of the composite sample of the Pittsburgh No. 8 fine-coal refuse material; data reported on a dry basis.

Size Fraction (mesh)	Weight (%)	Ash (%)	Total Sulfur (%)	Pyritic Sulfur (%)	Heat Value (BTU/lb)
+16	2.63	20.97	4.21	1.75	11790
16 x 28	12.30	16.92	3.97	1.30	12514
28 x 48	18.52	18.26	4.30	1.76	12179
48 x 65	7.72	24.72	4.59	2.03	11057
65 x 100	7.52	24.63	4.62	2.84	11032
100 x 200	12.07	26.16	7.04	5.11	10679
200 x 325	6.33	29.76	10.20	9.50	10331
325 x 400	1.43	32.94	10.30	9.60	9945
400 x 500	1.94	32.14	7.97	5.72	10164
-500	29.53	50.67	2.33	1.89	6532
Total	100.00	30.88	4.58	2.93	10000

Table 2.4. The physical and chemical properties of the composite sample of the Illinois No. 6 fine-coal refuse material; data reported on a dry basis.

Size fraction (mesh)	Weight (%)	Ash (%)	Total Sulfur (%)	Pyritic Sulfur (%)	Heat Value (BTU/lb)
+16	4.36	14.15	3.17	0.59	11063
16 x 28	5.62	12.67	3.01	0.45	11291
28 x 48	12.01	11.89	3.14	0.30	10929
48 x 65	8.35	12.29	3.38	0.30	11150
65 x 100	7.76	11.86	2.55	0.39	11354
100 x 200	13.95	13.36	2.72	0.55	11050
200 x 325	6.61	21.21	2.88	0.76	9956
325 x 400	1.96	24.06	2.50	0.70	9687
400 x 500	3.17	28.84	2.04	0.72	9065
-500	36.21	65.60	1.00	0.41	4626
Total	100.00	33.11	2.21	0.45	8593

Washability Tests

Washability analyses were conducted on seven particle size fractions (i.e., +16, 16 x 28, 28 x 48, 48 x 65, 65 x 100, 100 x 200, 200 x 325 mesh) obtained from the composite sample. The analyses were conducted using the ASTM static bath procedure and a lithium metatungstate solution as the medium. Each density fraction was rinsed, dried and prepared for ash and total sulfur analyses. The results of the washability tests regarding respective size fractions are presented in Tables 2.5-2.11 for Pittsburgh No. 8 and Tables 2.13-2.19 for Illinois No. 6, respectively.

Table 2.5. Washability results of the +16 mesh Pittsburgh No. 8 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	36.63	4.82	2.29	44.20	36.63	4.82	2.29	44.20
1.3 x 1.4	12.64	10.53	3.16	14.33	49.27	6.28	2.51	58.53
1.4 x 1.5	10.99	19.67	4.23	11.19	60.26	8.73	2.83	69.72
1.5 x 1.6	12.82	27.48	5.04	11.79	73.08	12.02	3.21	81.51
1.6 x 1.8	15.20	37.07	5.42	12.13	88.28	16.33	3.59	93.64
1.8 x 2.1	7.51	48.76	6.85	4.88	95.79	18.87	3.85	98.51
2.1	4.21	72.15	11.50	1.49	100.00	21.12	4.17	100.00
Total	100.00	21.12	4.17	100.00				

Table 2.6. Washability results of the 16 x 28 mesh Pittsburgh No. 8 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	40.38	3.92	2.08	46.69	40.38	3.92	2.08	46.69
1.3 x 1.4	23.10	10.63	3.11	24.85	63.47	6.36	2.45	71.54
1.4 x 1.5	10.14	20.88	4.57	9.66	73.62	8.36	2.75	81.20
1.5 x 1.6	9.39	29.33	5.39	7.99	83.00	10.74	3.05	89.19
1.6 x 1.8	10.23	39.54	6.20	7.45	93.24	13.90	3.39	96.63
1.8 x 2.1	5.26	53.15	7.40	2.97	98.50	15.99	3.61	99.60
2.1	1.50	77.88	9.99	0.40	100.00	16.92	3.70	100.00
Total	100.00	16.92	3.70	100.00				

Table 2.7. Washability results of the 28 x 48 mesh Pittsburgh No. 8 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	48.48	4.19	2.11	56.82	48.48	4.19	2.11	56.82
1.3 x 1.4	17.42	11.16	3.12	18.93	65.90	6.03	2.38	75.75
1.4 x 1.5	9.65	21.10	4.26	9.32	75.55	7.96	2.62	85.07
1.5 x 1.6	6.40	29.62	5.22	5.51	81.95	9.65	2.82	90.58
1.6 x 1.8	7.76	40.75	6.12	5.63	89.72	12.34	3.11	96.21
1.8 x 2.1	5.14	54.77	8.53	2.84	94.86	14.64	3.40	99.05
2.1	5.14	84.97	7.89	0.95	100.00	18.26	3.63	100.00
Total	100.00	18.26	3.63	100.00				

Table 2.8. Washability results of the 48 x 65 mesh Pittsburgh No. 8 fine-coal refuse material

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	48.21	3.75	2.02	61.64	48.21	3.75	2.02	61.64
1.3 x 1.4	14.44	10.90	2.73	17.09	62.65	5.40	2.18	78.73
1.4 x 1.5	6.77	19.98	3.90	7.20	69.42	6.82	2.35	85.93
1.5 x 1.6	4.78	28.08	5.04	4.57	74.20	8.19	2.52	90.50
1.6 x 1.8	5.68	38.25	6.01	4.66	79.88	10.33	2.77	95.15
1.8 x 2.1	6.08	55.56	9.12	3.59	85.96	13.52	3.22	98.74
2.1	14.04	93.25	7.13	1.26	100.00	24.72	3.77	100.00
Total	100.00	24.72	3.77	100.00				

Table 2.9. Washability results of the 65 x 100 mesh Pittsburgh No. 8 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	48.53	3.05	1.92	62.42	48.53	3.05	1.92	62.42
1.3 x 1.4	15.94	9.37	2.57	19.17	64.47	4.61	2.08	81.59
1.4 x 1.5	5.69	18.14	3.60	6.18	70.15	5.71	2.20	87.76
1.5 x 1.6	3.15	25.78	4.84	3.10	73.30	6.57	2.32	90.86
1.6 x 1.8	3.65	35.29	6.19	3.14	76.95	7.94	2.50	94.00
1.8 x 2.1	4.26	52.15	8.51	2.71	81.22	10.26	2.82	96.71
2.1	18.78	86.79	7.21	3.29	100.00	24.63	3.64	100.00
Total	100.00	24.63	3.64	100.00				

Table 2.10. Washability results of the 100 x 200 mesh Pittsburgh No. 8 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	50.90	2.90	1.98	66.94	50.90	2.90	1.98	66.94
1.3 x 1.4	12.90	9.20	2.43	15.86	63.80	4.17	2.07	82.79
1.4 x 1.5	4.07	16.70	3.25	4.59	67.87	4.92	2.14	87.39
1.5 x 1.6	2.49	23.29	4.05	2.59	70.36	5.57	2.21	89.97
1.6 x 1.8	2.04	31.89	6.10	1.88	72.40	6.31	2.32	91.85
1.8 x 2.1	1.81	46.71	9.51	1.31	74.21	7.30	2.49	93.16
2.1	25.79	80.41	15.90	6.84	100.00	26.16	5.95	100.00
Total	100.00	26.16	5.95	100.00				

Table 2.11. Washability results of the 200 x 325 mesh Pittsburgh No. 8 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	45.60	2.96	1.84	63.00	45.60	2.96	1.84	63.00
1.3 x 1.4	12.16	7.29	2.33	16.05	57.76	3.87	1.94	79.05
1.4 x 1.5	4.78	12.28	2.40	5.97	62.54	4.51	1.98	85.01
1.5 x 1.6	1.41	19.02	2.86	1.63	63.95	4.83	2.00	86.64
1.6 x 1.8	2.61	27.15	3.93	2.70	66.56	5.71	2.07	89.34
1.8 x 2.1	1.30	45.81	7.59	1.01	67.86	6.48	2.18	90.35
2.1	32.14	78.90	22.10	9.65	100.00	29.75	8.58	100.00
Total	100.00	29.75	8.58	100.00				

Particle size-by-size analyses of Illinois No. 6 fine coal refuse material reveal that, in the fine size fractions, ash contents considerably increase. For example, -500-mesh size material that accounts for 36.2% of the total weight has an ash content of 65.6% whereas the +200 mesh size fractions contain less than 14% ash. Distinctive accumulation of ash bearing materials below a specific size fraction may be advantageous during separation processes by simply treating that size fraction separately from the rest of the material. The distribution of sulfur, on the other hand, presents a rather peculiar behavior. Unlike the Pittsburgh No. 8 fine coal refuse sample, the sulfur does not concentrate in a specific size fraction but increases in the coarser particle size fractions. As indicated in Table 2.4, the pyritic sulfur contents do not vary significantly as the particle size changes. Furthermore, pyritic sulfur does not necessarily associate with ash bearing material. Almost even distribution of pyritic sulfur suggests that pyrite is finely distributed within the particles of all size fractions. Washability results show that liberation of inorganic sulfur occurs to some extent thus sulfur contents increase in the heaviest density fraction. This behavior may present difficulty in terms of reducing pyritic sulfur.

In Figure 2.2, the cumulative combustible recovery versus cumulative ash content relationship is plotted for each particle size fraction for Pittsburgh No. 8 refuse pond sample. It is clearly evident from the improved recovery-ash relationship that significant liberation of ash-bearing material occurs with decreasing particle size. In fact, the +48 mesh material contains greater than 10% near gravity material within the specific gravity range of 1.4 to 1.8 (Tables 2.5-2.7). This finding indicates that a highly efficient gravity-based separator will be needed to treat this fraction to ensure a high level of combustible recovery and/or the production of a high product grade. The amount of near gravity material substantially reduces to less than 5% in the 200 x 325 mesh particle size fraction, thereby suggesting that a moderately efficient separator may be sufficient for the treatment of the finer particle size fractions.

The washability test results presented in Tables 2.5-2.11 were combined to obtain the overall washability characteristics of the +325 mesh material comprising the Pittsburgh No. 8 fine-coal refuse. As shown in Table 12, slightly greater than 60% of the +325

mesh material has a specific gravity less than 1.4. This material has a relatively low ash content of 5.34%. However, the data also indicates that approximately 5% – 10% near gravity material exists in the 1.4 to 1.8 specific gravity range, thereby indicating a moderately difficult separation for gravity-based processes.

The data presented in Table 12 is graphically presented in Figure 2.3. The plot suggests that the ash content of the +325 mesh Pittsburgh No. 8 fine-coal refuse can be considerably lowered to such values as 9% on using gravity-based separation techniques with combustible recoveries above 90%.

Figure 2.2. Particle size-by-size washability curves obtained for the Pittsburgh No. 8 fine-coal refuse material.

Table 2.12. Composite washability test results of the +325 mesh Pittsburgh No. 8 fine-coal refuse.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	46.7	3.61	2.03	57.73	28.41	3.27	2.03	57.73
1.3 x 1.4	16.5	10.24	2.87	18.96	66.73	5.43	2.25	76.69
1.4 x 1.5	7.6	19.65	4.03	7.79	82.81	7.72	2.44	84.48
1.5 x 1.6	5.5	28.15	5.06	5.05	90.29	9.23	2.63	89.53
1.6 x 1.8	6.3	38.38	5.98	4.98	97.47	11.40	2.88	94.51
1.8 x 2.1	4.3	52.97	8.30	2.60	99.60	12.36	3.15	97.10
2.1	13.3	82.98	13.83	2.90	100.00	12.63	4.57	100.00
Total	100.0	22.09	4.57	100.00

Figure 2.3. The composite washability curve obtained from the particle size-by-size data for the +325 mesh Pittsburgh No. 8 fine-coal refuse material.

In Figure 2.4, the cumulative combustible recovery versus cumulative ash content relationship is plotted for each particle size fraction for Illinois No. 6 refuse pond sample. The plots for various size fractions suggest that there is not a particular tendency for the liberation of ash bearing material with respect to the particle size. For example, the lowest liberation occurs in +16-mesh particle size, as expected, while the highest liberation seems to be achieved at 28 x 48-mesh particle size fraction. On the other hand, it is evident from Figure 2.4 that the liberation degree of the 200 x 325-mesh particle size fraction lies closer to +16 mesh particle size fraction which contradicts with the general tendency of liberation as the particle size decreases. In general, near gravity material within the specific gravity range of 1.4 - 1.6 (Tables 2.13 - 2.19) is greater than 10%. This finding indicates that a highly efficient gravity-based separator will be needed to treat this coal to ensure a high level of product grade. However, at the specific gravity range above 1.6 the amount of near gravity material reduces below 10% and even 5%, thereby suggesting that a moderately efficient separation could be achieved ensuring a high level of combustible recovery.

The washability test results presented in Tables 2.13 - 2.19 were combined to obtain the overall washability characteristics of the +325-mesh material comprising the Illinois No. 6 fine-coal refuse. As shown in Table 2.20, greater than 70% of the +325-mesh material has a specific gravity less than 1.4. This material has a substantially low ash content of 3.91%. However, the data also indicates that approximately 3% - 7% near gravity material exist in the 1.6 to 1.8 specific gravity range, thereby indicating a moderately easy separation for gravity-based processes.

Table 2.13. Washability results of the +16 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	28.41	3.27	2.76	31.46	28.41	3.27	2.76	31.46
1.3 x 1.4	38.32	7.04	2.71	40.77	66.73	5.43	2.73	72.23
1.4 x 1.5	16.08	17.21	2.76	15.23	82.81	7.72	2.74	87.46
1.5 x 1.6	7.48	25.97	2.51	6.34	90.29	9.23	2.51	93.80
1.6 x 1.8	7.18	38.63	2.65	5.04	97.47	11.40	2.33	98.84
1.8 x 2.1	2.12	56.29	4.37	1.06	99.60	12.36	2.28	99.90
2.1	0.40	79.46	6.21	0.10	100.00	12.63	2.27	100.00
Total	100.00	12.63	2.76	100.00				

Table 2.14. Washability results of the 16 x 28 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	24.47	2.37	2.36	26.94	24.47	2.37	0.00	26.94
1.3 x 1.4	47.73	4.61	2.32	51.36	72.20	3.85	0.00	78.30
1.4 x 1.5	11.12	14.67	2.36	10.70	83.32	5.30	0.00	89.01
1.5 x 1.6	5.38	24.34	2.32	4.59	88.69	6.45	0.00	93.59
1.6 x 1.8	5.75	37.51	2.67	4.05	94.44	8.34	0.00	97.64
1.8 x 2.1	3.89	55.91	4.31	1.94	98.33	10.22	0.00	99.58
2.1	1.67	77.71	6.50	0.42	100.00	11.35	0.00	100.00
Total	100.00	11.35	2.50	100.00				

Table 2.15. Washability results of the 28 x 48 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	24.34	2.02	2.57	26.21	24.34	2.02	2.57	26.21
1.3 x 1.4	53.64	4.44	2.46	56.33	77.98	3.68	2.49	82.54
1.4 x 1.5	11.21	13.55	2.27	10.65	89.19	4.92	2.47	93.19
1.5 x 1.6	3.33	23.17	2.11	2.81	92.53	5.58	2.45	96.01
1.6 x 1.8	3.33	36.06	1.69	2.34	95.86	6.64	2.43	98.35
1.8 x 2.1	2.63	54.00	2.65	1.33	98.48	7.90	2.43	99.68
2.1	1.52	80.64	8.89	0.32	100.00	9.01	2.53	100.00
Total	100.00	9.01	2.53	100.00				

Table 2.16. Washability results of the 48 x 65 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	15.89	2.21	2.56	17.09	15.89	2.21	2.56	17.09
1.3 x 1.4	61.85	4.31	2.47	65.08	77.74	3.88	2.49	82.16
1.4 x 1.5	11.51	13.74	2.20	10.92	89.25	5.15	2.45	93.09
1.5 x 1.6	4.19	22.54	1.84	3.57	93.43	5.93	2.42	96.65
1.6 x 1.8	2.66	34.24	2.02	1.93	96.10	6.72	2.41	98.58
1.8 x 2.1	1.62	50.82	3.12	0.87	97.72	7.45	2.42	99.45
2.1	2.28	78.19	7.18	0.55	100.00	9.06	2.53	100.00
Total	100.00	9.06	2.53	100.00				

Table 2.17. Washability results of the 65 x 100 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	18.13	1.96	2.63	19.73	18.13	1.96	2.63	19.73
1.3 x 1.4	57.37	4.54	2.46	60.81	75.50	3.92	2.50	80.55
1.4 x 1.5	11.95	14.15	2.15	11.39	87.45	5.32	2.45	91.94
1.5 x 1.6	4.68	22.47	1.91	4.03	92.13	6.19	2.43	95.97
1.6 x 1.8	3.59	34.20	1.71	2.62	95.72	7.24	2.40	98.59
1.8 x 2.1	1.39	51.23	2.55	0.76	97.11	7.87	2.40	99.35
2.1	2.89	79.64	9.29	0.65	100.00	9.94	2.60	100.00
Total	100.00	9.94	2.60	100.00				

Table 2.18. Washability results of the 100 x 200 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	17.29	1.87	2.64	19.43	17.29	1.87	2.64	19.43
1.3 x 1.4	50.31	4.25	2.47	55.18	67.60	3.64	2.51	74.62
1.4 x 1.5	14.49	13.06	2.10	14.43	82.09	5.30	2.44	89.05
1.5 x 1.6	5.49	21.36	1.63	4.94	87.58	6.31	2.39	93.99
1.6 x 1.8	4.66	31.82	1.49	3.64	92.24	7.60	2.34	97.63
1.8 x 2.1	2.38	49.46	1.84	1.38	94.62	8.65	2.33	99.01
2.1	5.38	83.96	7.59	0.99	100.00	12.71	2.61	100.00
Total	100.00	12.71	2.61	100.00				

Table 2.19. Washability results of the 200 x 325 mesh Illinois No. 6 fine-coal refuse material.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	18.72	3.01	2.44	22.84	18.72	3.01	2.44	22.84
1.3 x 1.4	34.68	4.60	2.42	41.61	53.40	4.04	2.43	64.45
1.4 x 1.5	14.36	10.73	1.90	16.12	67.77	5.46	2.32	80.57
1.5 x 1.6	7.66	15.24	1.67	8.17	75.43	6.45	2.25	88.74
1.6 x 1.8	7.77	24.64	1.32	7.36	83.19	8.15	2.16	96.10
1.8 x 2.1	3.30	52.36	1.62	1.98	86.49	9.83	2.14	98.08
2.1	13.51	88.69	5.34	1.92	100.00	20.49	2.57	100.00
Total	100.00	20.49	2.57	100.00				

Table 2.20. Composite washability test results of the +325 mesh Illinois No. 6 fine-coal refuse.

Specific Gravity Fraction	Individual				Cumulative			
	Weight (%)	Ash (%)	Total Sulfur (%)	Comb. Rec. (%)	Weight (%)	Float Ash %	Total Sulfur (%)	Comb. Rec. (%)
1.3	20.3	2.27	2.57	22.52	20.3	2.27	2.57	22.52
1.3 x 1.4	50.7	4.56	2.46	54.84	71.0	3.91	2.49	77.36
1.4 x 1.5	12.8	13.63	2.21	12.58	83.8	5.39	2.45	89.93
1.5 x 1.6	5.1	21.73	1.93	4.56	89.0	6.34	2.42	94.49
1.6 x 1.8	4.6	33.14	1.85	3.49	93.6	7.66	2.39	97.98
1.8 x 2.1	2.4	52.67	2.74	1.30	96.0	8.79	2.40	99.28
2.1	4.0	84.19	6.94	0.72	100.0	11.82	2.58	100.00
Total	100.0	11.82	2.58	100.00				

The data presented in Table 2.20 is graphically presented in Figure 2.5. The plot suggests that the ash content of the +325 mesh Illinois No. 6 fine-coal refuse can be considerably lowered to values as low as 7.5% using gravity-based separation techniques with combustible recovery values above 95%. In addition, the relative separation density needed to achieve the 7.5% is within the range of 1.6 to 1.8 and, thus, would be easily achieved based on the low amount of near gravity material.

Figure 2.4. Particle size-by-size washability curves obtained for the Illinois No. 6 fine-coal refuse material.

Figure 2.5. The composite washability curve obtained from the particle size-by-size data for the +325 mesh Illinois No. 6 fine-coal refuse.

Release Analysis Tests

Release analysis is a method used to estimate the ultimate separation performance achievable by any froth flotation process for the treatment of a given material. In this study, the ultimate separation performance was determined for the -48 and -325-mesh particle size fractions. The Advanced Flotation Washability (AFW) form of the release analysis was used to determine the ultimate recovery-grade relationship. The analysis procedure is based on the traditional release procedure described by Dell (1954, 1964 and 1972) and the further modifications to the procedure achieved by Mohanty et. al (1997). As depicted in Figure 2.6, the first stage of the procedure employed a Denver flotation machine to separate the hydrophobic components from the hydrophilic components. In the first stage, a final tailings was produced after 4 stages of flotation. In the second stage, a batch operated, column flotation cell of 2 inches in diameter and around 5 feet in length was used to separate the material according to the degree of hydrophobicity and, thus overall grade. In all flotation tests, a polyglycol and No. 2 fuel oil were used as the frother and collector, respectively. The experimental conditions are given in Table 2.21 and 2.22 for Pittsburgh No. 8 and Illinois No 6 refuse pond samples, respectively.

The relatively low amount of reagent requirement for the flotation of Pittsburgh No. 8 fine-coal refuse sample indicates that it is an easy-to-float coal.

Figure 2.6 Schematic of the procedure used in the performance of the release analysis procedure.

Table 2.21. Experimental conditions applied in the release analysis procedure performed on the -48 and -325 mesh particle size fractions of the Pittsburgh No. 8 fine-coal refuse.

Particle Size (Mesh)	Variables	Stage 1	Stage2
-48	Sample weight (g)	739.2	238.5
	Slurry Volume (l)	2.5	1
	Collector dosage (lb./t)	5.28	---
	Frother dosage (lb./t)	1.74	---
-325	Sample weight (g)	523	102.7
	Slurry Volume (l)	2.5	1
	Collector dosage (lb./t)	6.32	---
	Frother dosage (lb./t)	1.35	---

Table 2.22. Experimental conditions applied in the release analysis procedure performed on the -48, -325 and 48 x 325 mesh particle size fractions of the Illinois No. 6 fine-coal refuse.

Particle Size (Mesh)	Variables	Stage 1	Stage2
-48	Sample weight (g)	486.2	127.5
	Slurry Volume (l)	2.5	1
	Collector dosage (lb./t)	31.6	---
	Frother dosage (lb./t)	1.7	---
-325	Sample weight (g)	551.6	138
	Slurry Volume (l)	2.5	1
	Collector dosage (lb./t)	29.3	---
	Frother dosage (lb./t)	1.4	---
48 x 325	Sample weight (g)	446	171.9
	Slurry Volume (l)	2.5	1
	Collector dosage (lb./t)	9.1	---
	Frother dosage (lb./t)	1.97	---

The release analysis data provided in Tables 23 and 24 and Figure 2.7 indicate that froth flotation has the potential to achieve highly efficient ash content reductions for both the -48 and -325 mesh material comprising the Pittsburgh No. 8 coal. The ash content of the -48 mesh material can be reduced from 37.8% to 10.1% while recovering above 90% of the combustibles. Product ash contents as low as about 4.4% can be obtained from the flotation of the -48 mesh material. The results obtained for the -325 mesh material indicates that lower product ash contents can be realized by froth flotation, which is reflective of the reduction in the amount of middling particles. Overall, the results are promising for the use of froth flotation for the treatment of the Pittsburgh No. 8 fine-coal refuse material.

Table 2.23 The results of release analysis obtained for the -48-mesh particle size fraction of the Pittsburgh No. 8 fine-coal refuse sample.

Products	Individual				Cumulative			
	Weight (%)	Ash (%)	Combust Recovery (%)	Heat Value (BTU/lb)	Weight (%)	Ash (%)	Combust Recovery (%)	Heat Value (BTU/lb)
C1	17.29	4.44	26.54	14367	17.29	4.44	26.54	14367
C2	1.95	6.86	2.91	14248	19.24	4.69	29.46	14355
C3	7.71	9.23	11.24	13610	26.95	5.99	40.70	14142
C4	18.72	10.75	26.84	13581	45.67	7.94	67.55	13912
C5	14.31	14.63	19.63	12762	59.98	9.54	87.18	13638
C6	2.41	24.77	2.91	11381	62.39	10.12	90.09	13550
C7	2.14	39.28	2.09	8598	64.53	11.09	92.17	
Tailings	35.47	86.26	7.83	1783	100.00	37.75	100.00	9087
Total	100.00	37.75	100.00	9271				

Table 2.24 The results of release analysis obtained for the -325 mesh particle size fraction of the Pittsburgh No. 8 fine-coal refuse sample.

Product	Individual				Cumulative			
	Weight (%)	Ash (%)	Combust Recovery (%)	Heat Value (BTU/lb)	Weight (%)	Ash (%)	Combust Recovery (%)	Heat Value (BTU/lb)
C1	6.00	5.25	10.98	14213	6.00	5.25	10.98	14213
C2	13.01	5.23	23.82	14217	19.00	5.24	34.79	14216
C3	9.70	5.91	17.64	14093	28.71	5.46	52.43	14174
C4	11.84	7.51	21.15	13804	40.55	6.06	73.59	14066
C5	4.12	12.48	6.96	12928	44.66	6.65	80.54	13961
C6	2.08	24.54	3.04	10921	46.74	7.45	83.58	13826
C7	2.39	49.81	2.32	7179	49.13	9.51	85.90	13503
Tailings	50.87	85.65	14.10	2574	100.00	48.24	100.00	7943
Total	100.00	48.24	100.00	7943

Figure 2.7. The separation performances achieved by release analysis for the -65 and -325 mesh particle size fractions of the Pittsburgh No. 8 fine-coal refuse sample.

The release analysis data provided in Tables 2.25 and 2.26 and Figure 2.8 indicate that ash rejections for both the -48 and -325 mesh material comprising the Illinois No. 6 coal present great difficulty. The collector dosages used were extremely high and they compared with the collector dosages used in Pittsburgh No. 8 refuse coal sample. Even with such high collector dosages only 40% and 58% of the combustibles were recovered in the first stage of the release analysis for -48 and -325-mesh material, respectively. Such a high amount of collector requirement could arise from the slime coating on the surface of coal particles. The associated clay mineral found in Illinois No. 6 coal is illite-montmorillonite weathered clays. Montmorillonite being an active clay mineral is generally used as drilling mud and for the absorption of undesired chemical species. Hence, it is highly likely that the coating of coal particles by the clay might have prevented successful flotation. This concept was also supported by an investigation into the effect of clay slimes on the coal flotation. Another possibility for the poor flotation could be excessive oxidation of coal particles that had been weathered for many years. Therefore, an additional flotation test was performed with 48 x 325-mesh particle size fraction to eliminate the effect of slime coating and to assess if the feeble flotation was a result of oxidation and the findings are presented in Table 2.27.

The ash content of the -48 mesh material can be reduced from 38.4% to 6% while recovering nearly 40% of the combustibles. Product ash contents as low as about 4.5%

can be obtained from the flotation of the -48 mesh material. A similar separation performance was obtained for the -325 mesh material.

When the results of 48 x 325 mesh and -325 mesh particle size fractions were combined, the composite -48 mesh separation performance is nearly equal to the results obtained when simultaneously floating the total -48 mesh material. However, the collector dosage needed to float the total -48 mesh material was 30% more than that used when floating the 48 x 325 and -325 mesh particle size fractions separately.

Combustible recoveries obtained for both coal samples are seen to be markedly different. It is also worth noting that the collector requirement for Pittsburgh No. 8 coal sample was considerably lower than that needed for Illinois No. 6 refuse coal sample.

Table 2.25. The results of release analysis obtained for the -48-mesh particle size fraction of the Illinois No. 6 fine-coal refuse sample.

Products	Individual					Cumulative				
	Weight (%)	Ash (%)	Total Sulfur (%)	Heat Value BTU/lb	Comb. Recov. (%)	Weight (%)	Ash (%)	Total Sulfur (%)	Heat Value BTU/lb	Comb. Recov. (%)
C1	5.29	4.52	2.56	13185	8.19	5.29	4.52	2.56	13185	8.19
C2	8.35	5.84	2.62	12809	12.76	13.64	5.33	2.60	12955	20.95
C3	2.86	6.88	2.68	12407	4.32	16.50	5.60	2.61	12860	25.27
C4	9.73	6.90	2.71	12000	14.70	26.22	6.08	2.65	12541	39.96
Tailings	73.78	49.85	1.71	6694	60.04	100.00	38.37	1.96	8227	100.00
Total	100.00	38.37	1.96	8227	100.00					

Table 2.26. The results of release analysis obtained for the -325-mesh particle size fraction of the Illinois No. 6 fine-coal refuse sample.

Products	Individual					Cumulative				
	Weight (%)	Ash (%)	Total Sulfur (%)	Heat Value BTU/lb	Comb. Recov. (%)	Weight (%)	Ash (%)	Total Sulfur (%)	Heat Value BTU/lb	Comb. Recov. (%)
C1	1.99	5.09	1.83	13588	4.79	1.99	5.09	1.83	13588	4.79
C2	3.68	6.03	1.80	13282	8.76	5.67	5.70	1.81	13390	13.55
C3	5.67	7.13	2.03	13000	13.34	11.35	6.41	1.92	13195	26.89
C4	3.03	8.03	2.02	12719	7.05	14.38	6.75	1.94	13095	33.94
C5	2.61	8.97	1.89	12367	6.02	16.99	7.10	1.93	12983	39.96
C6	1.40	10.64	1.89	11717	3.16	18.38	7.36	1.93	12887	43.12
C7	3.43	12.34	1.90	11261	7.61	21.81	8.15	1.93	12631	50.72
C8	3.21	16.00	1.93	10415	6.82	25.02	9.15	1.93	12347	57.55
Tailings	74.98	77.64	0.90	3083	42.45	100.00	60.51	1.16	5401	100.00
Total	100.00	60.51	1.16	5401	100.00

Figure 2.8. The separation performances achieved by release analysis for the -48 and -325 and 48 x 325-mesh particle size fractions of the Illinois No. 6 fine-coal refuse sample.

Table 2.27. The results of release analysis obtained for the 48 x 325-mesh particle size fraction of the Illinois No. 6 fine-coal refuse sample.

Products	Individual			Cumulative		
	Weight (%)	Ash (%)	Comb. Recov. (%)	Weight (%)	Ash (%)	Comb. Recov. %
C1	8.26	6.59	8.96	8.26	6.59	8.96
C2	19.34	6.94	20.89	27.60	6.84	29.86
C3	29.99	8.28	31.94	57.59	7.59	61.80
C4	11.85	9.65	12.43	69.44	7.94	74.23
C5	19.91	11.47	20.46	89.35	8.73	94.70
Tailings	10.65	57.11	5.30	100.00	13.88	100.00
Total	100.00	13.88	100.00			

SUMMARY AND CONCLUSIONS

The work conducted during this reporting period involved the completion of Task 1.0 through characterization of Illinois No. 6 fine coal refuse pond sample, production of slurry samples for each of the cooperating research groups, initiation of the test program to quantify the operating parameter effects of the Falcon concentrator when using water-only as the medium, refuse remediation testing using the Falcon concentrator, sample characterization for dewatering purposes and the initial evaluation of vacuum and pressure filtration. The test results obtained to date have generated the following summary and conclusions:

- a. The as-received Pittsburgh No. 8 fine-coal refuse material contained about 30% -500 mesh material and less than 3% +16 mesh. The Illinois No. 6 fine-coal refuse material head sample contained about 36% -500 mesh material and less than 5% +16 mesh.
- b. The heating value of the Pittsburgh No. 8 fine-coal refuse is at around 10,000 Btu/lb. This is reflective of an overall ash content of 31.6% and a pyritic sulfur content of 2.93%. The heating value of the Illinois No. 6 fine-coal refuse is relatively lower than that of Pittsburgh No. 8 fine-coal refuse at around 8600 Btu/lb. This is reflective of an overall ash content of 33.1%, a total sulfur content of 2.21% and a pyritic sulfur content of 0.45%.
- c. The washability data obtained for the Pittsburgh No. 8 refuse indicate that the cleanability can be classified as moderately difficult using gravity-based processes, especially for the +48 mesh particle size fraction which contains greater than 10% near gravity material within the specific gravity range of 1.4 to 1.8. Significant liberation of the ash-bearing material is apparent as the particle size is reduced.
- d. The washability data obtained for the Illinois No. 6 refuse indicate that the cleanability can be classified as moderately easy using gravity-based processes, especially for the 1.6 - 1.8 specific gravity range which contains less than 10% near gravity material. No trend was observed with the ash content as the particle size decreases.
- e. Flotation experiments suggest that the Pittsburgh No. 8 material is relatively easy to float. Release analyses on the -325 mesh material indicate the ability to produce a clean coal concentrate containing less than 5% ash from a feed having nearly 50% ash.
- f. Flotation experiments suggest that the Illinois No. 6 material is difficult to float. Release analyses conducted on the -48 mesh material indicate that a clean coal concentrate containing about 6% ash could only be produced with 40% mass yield from a feed having nearly 38% ash.

ACKNOWLEDGEMENTS

The authors appreciate the financial support of the Federal energy technology Laboratory, and the Office of Coal Development and Marketing of the Illinois Department of Commerce and Community Affairs. The cooperation and assistance of Peabody Coal Company, Consolidation Coal Company staff is sincerely acknowledged.

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Chapter 3

Hydraulic Particle Gravity and Size Separation

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July 2000

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SUMMARY OF WORK

Development and Demonstration of Integrated Carbon Recovery Systems from Fine Coal Processing Waste

(Summary of work completed as part of Phase I Project)
Task 4.1 – Studies on Hydraulic Classification

Tasks Proposed

1. A Plackett-Burman test program will be conducted on one of the refuse pond samples to identify the critical operating parameters of the Hydrofloat process.
Status: A test program was performed over a range of process variable values to determine their effect. This task was completed.
2. A Box-Behnken test program will be conducted on one of the refuse pond samples to optimize the critical process parameters of the Hydrofloat.
Status: Due to the limited effectiveness of the air bubble injection on this particular sample and the limited sample supply, the Box-Behnken program was substituted with additional teeter-bed experiments.
3. The samples collected at five different points along the optimum yield versus product grade curve of the Hydrofloat will be analyzed on a particle size-by-size basis for ash, total and pyritic sulfur, and Btu contents.
Status: All the particle size, ash and total sulfur analyses have been completed and the remaining analysis are being performed.
4. Tests using the optimum operating parameter values will be performed on the second refuse sample.
Status: This task was completed using teeter bed experiments.
5. An apex (Cyclowash) washer will be evaluated which has the ability to achieve a 325 mesh particle size cut in a single (rougher) stage with minimum by-pass.
Status: Completed

Additional Tasks Accomplished

1. Since the teeter-bed provided near perfect cleaning performance, the several additional teeter bed experiments were conducted.
2. A detailed experimental program was performed at an operating preparation plant to obtain more meaningful data for use in analyzing the overall performance improvement.

ABSTRACT

The integrated fine coal cleaning circuits being developed in this project employ hydraulic process units to achieve gravity-based separations and particle size classification. A teeter-bed unit that has the ability to inject air bubbles for coarse particle recovery was evaluated for the use as a primary cleaning unit. The organic efficiencies achieved from the treatment of 16 x 100 mesh particle size fraction in a Pittsburgh No.8 fine coal refuse were greater than 90% over the product ash content range of 7.56% to 11.81% yielded from the teeter-bed. To deslime the final clean coal product, a Krebs classifying cyclone was equipped with a Cyclowash system that replaces the feed pulp water reporting to the underflow stream with clean water. As a result, the by-pass was reduced from a value of 18% from a conventional cyclone to a value of 8% from the Cyclowash system. Further manipulation of the process parameter values yielded a relatively low 3.8% by-pass of ultrafine material.

INTRODUCTION AND PROBLEM STATEMENT

Teeter-Bed Gravity Separation

Teeter-bed separators have recently received significant interest for the application of carbon recovery from active fine coal streams and refuse ponds. Using an upward current of teeter water to suspend middling particles entering through the feed stream, an autogenous medium is formed through which only the heavy particles can pass and report to the underflow. As such, excellent process efficiencies and low separation densities that are similar to dense medium processes have been achieved using teeter beds to treat 16 x 100 mesh coal (Reed et al., 1995; Drummond et al., 1998). However, conventional systems have an inherent problem of losing coarse coal to the tailings stream (Honaker, 1996; Galvin et al., 1998).

To alleviate the problem of coarse coal loss, Eriez Magnetics developed a teeter bed system commercially known as the Hydrofloat that employs the injection of air bubbles. Upon entry of the air bubbles into the bottom of the cell (Figure 3.1), the rising bubbles collide and attach to the settling coarse coal particles. The air bubble-coal particle aggregate thus has a sufficiently low density to allow the teeter water to carry the aggregate upward and into the product overflow stream. Significant improvements in the separation performance have been realized in preliminary tests involving the treatment of phosphate (Kohmuench and Luttrell, 2000) and fine coal (Mankosa et al., 2000).

Figure 3.1. Schematic of the Hydrofloat density separator developed by Eriez Magnetics.

Water-Injection Classifying Cyclones

Efficient classification in the desliming process is a requirement to obtain a final clean coal product from enhanced gravity separators without the use of a froth flotation process. Hydrocyclones are the most widely used device for desliming purposes in the mineral and coal processing industry. It is well known that, in a hydrocyclone, a fraction of the feed material reports to underflow stream thereby reducing the classification efficiency. This reduction in efficiency can be quantified in terms of percentage by-pass, which is schematically defined in Figure 3.2. The presence of fines in the underflow is attributed to the water reporting with the underflow product (Wills, 1997). Therefore, smaller the volume of underflow water, less will be the fines associated with it and better will be the sharpness of separation. The volume of underflow water can be curtailed by reduction in the underflow orifice or by a restriction in underflow line and many methods have been listed by Bradley (1965). All these require the addition of a special valve downstream to create back pressure and are subject to the disadvantage of wear, requiring extra maintenance.

Hydraulic water addition through the apex, to displace the underflow liquid has been used to increase the sharpness of separation. The process was first used in the paper industry to reduce loss of good fiber with the rejected dirt as noted by Bradley (1965). Dahlstrom

Figure 3.2 Partition curve showing the reduced classification efficiency resulting from the by-pass of ultrafine particles to the cyclone underflow stream.

(1954) has successfully adopted this technique for desliming of mined product. Kelsall and Holmes (1960) first demonstrated better sharpness of classification, in a 3" cyclone wherein 48% of the -10 micron sand in the feed reporting to underflow in normal operation was reduced to 11.5% on water injection. The system is now patented and is commercially available from Krebs Engineers as the K H Cyclowash. However, technical details of its operation, under various design and operating conditions are sparse.

Table 3.1 shows the effect of water injection in a 4" Krebs cyclone classifying silica fines (Patil and Rao, 1999). Water injection reduced the percentage of particles smaller than 38 microns in the underflow from 23.14% to 7.10%. It is clear that the truncated cone plays a major role in reduction of fines to the underflow stream. The magnitude of the reduction depends on the type of material being classified and various cyclone-operating parameters. These results show that a water injection cyclone operating under optimal conditions may provide significantly better classification efficiency in the removal of -325 mesh particles compared to conventional units.

Table 3.1. Effect of water injection and truncated cone on the percentage of fines reporting to underflow (Patil and Rao, 1999).

Particle Size (μm)	No truncated cone		With truncated cone	
	No injection	With injection	No injection	With injection
- 212	83.91	84.73	80.42	71.93
-150	68.73	68.44	66.44	48.57
- 106	55.39	53.33	50.48	30.27
- 75	44.54	40.87	39.35	18.17
- 53	35.42	30.57	32.32	11.02
- 38	27.85	22.48	23.14	7.11
- 27	21.28	16.00	17.11	4.85
-19	16.29	11.58	12.80	3.69
- 9.5	10.39	7.20	8.09	2.80

GOALS AND SPECIFIC OBJECTIVES

The goals of this task were to evaluate and quantify the separation efficiencies of a teeter-bed separator with and without the injection of air bubbles and to investigate the benefits of using water-injection into the apex of a classifying cyclone. The teeter-bed separator serves the role as the initial coal cleaning process in the water-only integrated circuit that was evaluated as part of this project. As such, process efficiency is more critical. In addition, partition curve information is needed from both the teeter-bed and Cyclowash system to allow effective planning of circuit integration through simulation.

PERTINENT LITERATURE REVIEW

One of the most significant developments in coal preparation during the past decade has been the development and commercialization of column flotation technologies. Column flotation generally allows a more efficient recovery of fine coal particles (i.e., $-150 \mu\text{m}$) than conventional flotation while providing improved selectivity through the use of wash water and relatively deep froth depths. As a result, the installation of flotation columns in operating preparation plants have resulted in significant economic gains due to an improved product quality produced from the fine coal fraction and improved mass yield values (Brake and Eldridge, 1996; Mohanty et al., 1999). In some cases, this benefit allows greater mass recoveries from the coarse and intermediate particle size fractions (Yoon et al., 1996; Honaker et al., 1999).

Despite the success of column flotation, a significant disadvantage of any froth flotation process is the inherent inefficiency in the selectivity achieved on fine coals containing significant amounts of middling and/or coal pyrite particles. For this reason, gravity-based separations provide superior or equal separation performances compared to froth

flotation processes depending upon sufficient gravitation forces, retention time and coal characteristics (Adel et al., 1989; Wang et al., 1992; Mohanty et al. 1998). Based on this fact, maximizing the use of gravity-based processes for the treatment of fine coal would be advantageous for optimizing the rejection of impurities and the undesirable trace elements from coal while achieving the ultimate mass recovery values.

In terms of gravity-based separations for fine coal cleaning, spiral concentrators have received the most attention during recent years. Their popularity with coal operators for treating the nominally 1 mm x 150 μ m coal is derived from low capital and operating costs and operational simplicity. In addition, spiral concentrators inherently do not bypass light coal to the tailings stream. However, a deficiency of spiral units is a limit on the ability to achieve separations at low relative density (d_{50}) values. The lowest d_{50} reported for spiral concentrators used for primary cleaning only has been around 1.75 while achieving moderate separation efficiencies as indicated by probable error (E_p) values of around 0.15 to 0.18. Recent research has found that spiral concentrators can be used in a circuitry arrangement to achieve lower d_{50} values of around 1.60, which has led to significant economic gains for an operating coal preparation plant (Luttrell et al., 1999). However, the circuit E_p values remained in the same range as a primary spiral and a significant number of secondary spirals were needed in the overall circuit.

An alternative to spirals is the use of hindered-bed classifiers, which have been found to provide effective gravity-based separations for fine coal cleaning (Mankosa et al., 1995; Reed et al., 1995; Honaker, 1996). In fact, Nicole and Drummond (1997) have reported that hindered-bed units can be used to achieve low d_{50} values of around 1.40 while achieving E_p values below 0.10 for the treatment of 1 mm x 150 μ m coal, which indicates excellent separation efficiency. As a result of the preliminary study, a 75 tonne/hr unit has been successfully installed in an operating preparation plant, from which, the reported efficiency values have been validated (Drummond et al., 1998).

For the gravity-based cleaning of -150 μ m coal, enhanced gravity separators (EGS) have achieved promising results (Honaker et al., 1995; Riley et al., 1995; Luttrell et al., 1995; Honaker, 1998; Mohanty and Honaker, 1999). Relatively low d_{50} values of around 1.5 to 1.6 and E_p values of about 0.12 have been achieved with continuously operating units at throughput capacities up to 75 tonne/hr. A direct comparison of separation performance data generated from a flotation column and an EGS unit found that the EGS unit provided superior ash and sulfur reductions for the 150 x 44 μ m particle size fraction (Honaker, 1998). However, the -44 μ m material was more effectively treated in the flotation column, which is likely due to the inability of the ultrafine material move independently through the fluid. Thus, froth flotation or an efficient desliming device is needed to provide final cleaning of the EGS product.

EXPERIMENTAL STUDIES AND DATA ANALYSIS

Teeter-Bed Separator

A 2 x 8 in² Hydrofloat unit was provided by Eriez for the test program in this investigation. Teeter water was injected near the bottom of the vessel in a downward direction to ensure uniform upward movement of the water through the fluidized particle bed. However, to prevent air entrapment along the top of the spray bar, the teeter water and air bubbles were injected in an upward direction when testing the concepts associated with the Hydrofloat. A pressure transducer and a pinch valve were used under manual control to manipulate the level of the fluidized particle bed, which was generally maintained within about 8 inches of the overflow launder.

The operating parameters and parameter ranges evaluated in the test program were:
Teeter Water Rate: 1.5 – 3.0 liters/min; Volumetric Feed Rate: 1.5 – 3.5 liters/min
Aeration Rate: 0.1 – 0.5 liters/min.

Frother concentration was maintained at 10 ppm. Due to the relatively large capacity of the unit and a limited sample supply, the number of tests conducted were limited. The underflow tailings stream was operated intermittently due to the need of a relatively large valve to prevent particle bridging and the limited volume of tailings material entering in the feed stream. An outline of the test program conducted is provided in Table 3.2.

Table 3.2. Test program conducted on the Hydrofloat separator.

Test Number	Teeter Water (lpm)	Volumetric Feed Rate (lpm)	Frother Concentration (ppm)	Aeration Rate (lpm)
1	1.5	2.25	10	0.3
2	2.0	2.25	10	0.3
3	2.5	2.25	10	0.3
4	2.0	2.25	10	0.5
5	2.0	1.50	10	0.3
6	1.5	1.50	10	0.3
7	2.5	1.50	10	0.3
8	2.0	3.00	10	0.3
9	1.5	3.00	10	0.3
10	2.5	3.00	10	0.3
11	2.0	2.25	---	---
12	2.5	2.25	---	---
13	3.0	2.25	---	---
14	1.5	2.25	---	---
15	2.0	1.50	---	---
16	2.5	1.50	---	---
17	3.0	2.25	---	---
18	2.0	3.00	---	---
19	2.5	3.00	---	---

The characteristics of the coal refuse samples treated during the Hydrofloat test program are shown in Tables 3.3 and 3.4. The samples were prescreened with a 16 mesh sieve to remove oversize material that could result in plugging problems during the tests. After prescreening, the solids content of the feed slurry was adjusted by the addition of water to a value of approximately 35% by weight. Typical actual values of the feed slurry are provided in Tables 3.3 and 3.4.

Table 3.3 Particle size-by-size analyses of the Pittsburgh No. 8 refuse.

Size Fraction (mesh)	Weight (%)	Ash (%)	Total Sulfur (%)	Solids Content (%)
+48	31.26	16.6	4.29	37.11
48 x 100	21.39	27.01	4.17	
-100	47.35	43.58	5.8	
Total	100.00	31.60	4.98	

Table 3.4 Particle size-by-size analyses of the Illinois No. 6 refuse.

Size Fraction (mesh)	Weight (%)	Ash (%)	Solids Content (%)
+48	14.97	14.09	35.26
48 x 100	16.29	13.50	
-100	68.74	48.80	
Total	100.00	37.85	

Samples collected from the process streams during the test program were wet screened into particle size fractions of +48, 48 x 100 and -100 mesh. The material in each size fraction was weighed and assayed for ash and total sulfur contents using ASTM procedures. Repetitive analyses and standards were used to ensure data accuracy.

Krebs Cyclowash

The Cyclowash used in this investigation was installed into a 4-in diameter cyclone having a cone angle of 12° (Figure 3.3). The essential features of the Cyclowash are the water injection facility at the apex of the cyclone and the truncated cone. The truncated cone is situated slightly above the apex of the cyclone thus dividing the cyclone into two. In the upper section of the cyclone (above truncated cone) primary classification of feed material takes place. The classified coarse material enters the chamber below truncated cone, where water is introduced tangentially. The injected water displaced the very fine particles to the overflow, thus achieving secondary classification. Hence, Cyclowash provides a two stage classification in a single stage operation.

Due to the addition of water, operating and testing the unit in a laboratory environment would have been difficult. Therefore, the test program was conducted in the TVA's

Paradise coal preparation plant located in Drakesboro, Kentucky, which treats coal from several Illinois Basin seams. The cyclone and Cyclowash system was fed from a 4-inch diameter pipe containing a split stream from the main froth flotation feed, which was derived from the overflow of a hydrocyclone bank designed to achieve a nominal 100 mesh particle size separation.

Figure 3.3. Schematic diagram of Krebs Cyclowash.

The test program was conducted over a two day operating period in the plant and was designed to investigate the effect of the Cyclowash operating parameters (i.e., truncated cone diameter and injection water flow rate) and the typical classifying cyclone parameters (i.e., feed injection pressure, apex diameter and vortex finder diameter). A five gallon sample of each process stream was collected from each test and subsequently split into representative 2000 ml lots using a rotary splitter.

Representative samples from the process stream in each test were analyzed for solids content by weight and ash content. Particle size analyses were performed using a Microtrac. Periodic particle size analysis of a standard as well as repetitive sample analyses was used to ensure accuracy of the data.

RESULTS AND DISCUSSION

Hydrofloat/Teeter-Bed Gravity Separations

The separations performances achieved on the +48 mesh particle size fraction of the Pittsburgh No.8 refuse by the Hydrofloat unit with and without air assistance are compared with the gravity washability data obtained on the same size fraction in Figure

3.4. As shown, the teeter bed without air assistance provided excellent separation performances over the entire range of product ash values. In fact, some of the results appear to be superior to the washability analysis data, which may be explained by experimental error with the intermittent tailing discharge. The ash content was reduced from nearly 17.0% to values between 5.89% and 11.03% while maintaining organic efficiency values (=actual recovery/theoretical recovery) greater than 90%. The corresponding ash rejection was between 42.4% and 85.3%. Approximately 53% of the total sulfur was rejected in a typical case which resulted in a sulfur reduction from 4.30% to 2.50%.

It is also apparent from Figure 3.4 that the injection of air bubbles in the Hydrofloat unit had little benefit for the treatment of the +48 mesh material. This finding is likely due to the prescreening of the sample at 16 mesh which left no oversize material and the high efficiency level of the teeter bed in the treatment of the remaining +48 mesh material.

Figure 3.4. Separation performances achieved on the +48 mesh Pittsburgh No. 8 material by the Hydrofloat unit operated as a normal teeter-bed and with air bubble injection. A comparison with washability analysis data is provided.

Figure 3.5 also shows the high level of process efficiency achieved by the cleaning of the entire +100 mesh material comprising the Pittsburgh No. 8 refuse. With the exception of only two tests, the ash content of the 48 x 100 mesh material in the tailings stream was 80% or greater. These high tailings assays were obtained while reducing the ash content in this fraction from 22.0% to values between 9.69% to 13.20%.

A visual observation noted during the tests was that the stratification of the teeter bed improved with an increase in time. Since a relatively low amount of tailings were being withdrawn, the retention time of a particle in the fluidized bed was an hour or more. For this reason, each test required approximately 2 to 3 hours of operating time. During this period, the purification of the particle bed with only the heaviest particles was visually noticeable. As such, it is believed that separation performance from a teeter bed may be dependent on the amount of coarse reject material in the feed. Feed coal containing low amounts of coarse rejection will provide maximum particle retention time in the fluidized particle bed and thus realize the best separation efficiency.

Figure 3.5. Separation performances achieved on the +100 mesh Pittsburgh No. 8 material by the Hydrofloat unit operated as a normal teeter-bed and with air bubble injection. A comparison with washability analysis data is provided.

Teeter water flow rate was used to vary the product grades produced. In Table 3.5, the results were obtained by water flow rates of 2.0, 2.5 and 3.0 liters/min, respectively. One should note that teeter water flow rate has the greatest effect on the coarsest size fraction in terms of improving product quality and reducing recovery. In addition, the particle size-by-size results reveal that significant reductions in sulfur are realized by the teeter-bed for particle sizes below -100 mesh. The sulfur content of the -100 mesh tailings are as high as 26.7%, which made the samples appear golden in color. The ultimate sulfur reduction in the -100 mesh fraction was typically from 5.8% to 4.8%.

Similar results were obtained from the treatment of the Illinois No. 6 refuse sample as shown in Table 3.6.

Table 3.5. Particle size-by-size separation performance results achieved from the treatment of the Pittsburgh No. 8 refuse material by the Hydrofloat separator.

Test Number	Particle Fraction (mesh)	Ash (%)		Total Sulfur (%)		Combustible Recovery (%)
		Product	Tailings	Product	Tailings	
1	+48	5.89	36.05	2.15	5.84	56.14
	48 x 100	9.92	76.76	2.86	6.71	87.16
	-100	43.36	76.92	4.31	15.40	98.07
2	+48	8.56	50.23	2.70	7.25	88.49
	48 x 100	11.25	83.73	3.10	6.24	95.15
	-100	42.39	70.44	4.77	26.70	97.78
3	+48	11.03	52.72	2.93	7.66	92.43
	48 x 100	12.79	82.59	3.55	8.22	95.14
	-100	42.33	68.67	4.98	26.80	97.36

Table 3.6. Particle size-by-size separation performance results achieved from the treatment of the Illinois No. 6 refuse material by the Hydrofloat separator.

Test Number	Particle Fraction (mesh)	Ash (%)		Ash Rejection (%)	Mass Yield (%)	Combustible Recovery (%)
		Product	Tailings			
1	+48	5.52	53.73	67.79	82.22	90.43
	48 x 100	7.36	84.67	49.81	92.06	98.59
	-100	48.36	75.81	2.49	98.40	99.24
2	+48	7.09	56.83	56.72	85.95	92.94
	48 x 100	9.41	87.92	33.23	94.94	99.29
	-100	48.67	80.00	0.05	99.97	99.99

Cyclowash Particle Size Classification

Conventional classifying cyclone tests were performed using a 4 in diameter cyclone fitted with a 1 in diameter vortex finder and a 0.6875 in apex. The feed pressure was set a 25 psi. The results are compared with those obtained after the addition of the Cyclowash system in the form of partition curves in Figure 3.6. The Cyclowash water rate was 10 gallons/min and the truncated cone diameter was 1 inch. As shown, the Cyclowash system had two main effects, i.e. 1) increase in the particle size cut point (d_{50}) from about 20 to 28 μm and 2) substantial reduction in the amount of ultrafine by-pass from nearly 18% to 8%. Considering that a substantial amount of the -100 mesh coal is typically -10 μm , the improvement in the amount of by-pass allowed is substantial. The repeat of the Cyclowash, which occurred at a different time during the two-day in-plant testing program, shows good repeatability of the performance.

Figure 3.6 A comparison of the classification partition curve achieved with and without the Cyclowash system; injection water = 10 gpm & 1 in diameter cone.

Figure 3.7 compares the effect of feed injection pressure on the conventional and Cyclowash classification performance. The largest variance occurs from the use of 20 psi pressure where the by-pass amount was reduced from 12% to about 4% with a d_{50} of 25 μm . The relative minor improvement at 30 psi may be due to the increased volume flow rate through the apex and the insufficient amount of Cyclowash water used (=10 gpm).

Figure 3.7. A comparison of the feed injection pressure effect on the classification efficiency achieved with and without the Cyclowash system.

Decreasing the vortex finder diameter ultimately results in an increase in the amount of feed pulp water reporting to the apex of the cyclone. As a result, an increase in the amount of by-pass occurs unless the Cyclowash water rate is correspondingly increased. Figure 3.8 shows the increase in by-pass when the Cyclowash water rate is maintained at the same value. However, when the water rate is increased to 10 gpm upon increasing the vortex finder, the overall process performance is maintained at a near equal value. One should note that Figure 3.8 also shows that a nearly equal d_{50} can be achieved at a lower Cyclowash water rate by decreasing the vortex finder diameter.

Figure 3.8 The effect of vortex finder diameter on the amount of Cyclowash water needed to minimize ultrafine particle by-pass.

SUMMARY AND CONCLUSIONS

In this investigation, the use of a teeter-bed separator with and with air bubble injection was evaluated to quantify the separation efficiency achievable from the treatment of two fine coal refuse pond samples. The teeter-bed unit is the primary cleaning unit in the water-only integrated circuit being developed in the overall project. The production of a final product from both the dense medium and water-only circuits require efficient particle size classification to remove the ultrafine slime material (-325 mesh), which will be either discarded as waste or treated using a froth flotation process. The Krebs Cyclowash unit was evaluated for this purpose in an in-plant testing program that was performed over two days of plant operation.

The following conclusions were derived from the results obtained from the on-going investigation into hydraulic separations:

1. Teeter-bed separators provided an efficient cleaning of 16 x 100 mesh coal. For the Pittsburgh No. 8 coal sample, the ash content was reduced from over 20% to

about 10.0% while maintaining a high combustible recovery of nearly 90%. This performance is near the gravity washability curve as indicated by organic efficiency value greater than 95%. The production of lower product ash contents resulted in a moderate decline in organic efficiency. For the Illinois No. 6 refuse material, product ash contents below 7% were achieved using the teeter bed unit while recovering approximately 95% of the combustible material in the +100 mesh particle size fraction.

2. For the coal sample in this study, the injection of air bubbles did not provide an apparent benefit in the separation process. This finding was likely due to the near optimal performance of the teeter bed on the 16 x 100 mesh material and the oxidation state of the refuse material.
3. The Cyclowash system provided a substantial reduction in the amount of ultrafine material reporting to the underflow stream of a classifying cyclone treating nominally -100 mesh material. Under similar operating conditions, the amount of by-pass was reduced from 18% to about 8%. At a feed pressure of 20 psi, a mean particle size separation (d_{50}) of 25 μm was achieved while by-passing less than 4% of the ultrafine material using the Cyclowash system. The amount of water injection required reportedly a function of the amount of water normally entering the underflow discharge stream. Further analysis of the data is expected to result in the identification of operating conditions that may lead to improved performances.

RECOMMENDATIONS FOR FUTURE RESEARCH

The high capacity of teeter-bed separators and the problems associated with particle bridging in the underflow discharge stream limited the ability to operate under ideal conditions. In addition, the benefits of air injection were not realized due to the limit on the upper particle size entering the unit through the feed stream and the oxidization state of the refuse material. The full benefit of the unit will be better quantified through an in-plant test program where adequate feed material is available. This is a proposed objective in Phase II of this investigation.

The test program on the Cyclowash system was performed on a 4-inch diameter classifying cyclone. Due avoid the problems of plugging in a plant environment, a more ideal unit size would be 10 inches in diameter. Thus, it is recommended that an in-plant testing of a 10-inch diameter unit be performed to evaluate overall feasibility and effectiveness. The benefits of the Cyclowash unit will also be economically significant in other mineral processing applications, such as in the grinding circuits of complex ores.

ACKNOWLEDGEMENTS

In addition to the funding support by the U. S. Department of Energy, the principal investigator greatly appreciates the support provided by Eriez Inc through the use of the Hydrofloat separator and the technical assistance. Sincere gratitude is also expressed toward personnel at the Tennessee Valley Authority (TVA) Paradise coal preparation plant in particular Mr. Nisheeth Singh and the research staff at the CAER including Dr. B. K. Parekh and Mr. John Wiseman for their assistance throughout the various test programs. Also, sincere appreciation is expressed to Southern Illinois University, Dr. D. P. Patil and Mr. Amit Patwardhan for providing assistance in arranging the test program.

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Chapter 4

Enhanced Gravity Concentration

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July 2000

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SUMMARY OF WORK

Development and Demonstration of Integrated Carbon Recovery Systems from Fine Coal Processing Waste

(Summary of work completed as part of Phase I Project)

Task 2 – Enhanced Gravity Separation

Tasks Proposed

Task 2.1 Identification of crucial operation variables and optimization of Water-Only and Dense-Medium Falcon Processes

All items included in the original proposal were addressed

Task 2.2 Evaluation of the water-only and dense-medium Falcon processes for different feed characteristic refuse pond samples

All items included in the original proposal were addressed.

Task 2.3 Evaluation of water-only falcon process for separation of clay-rich fraction from acid generating materials

All items included in the original proposal were addressed.

Task 2.4 Process automation and control

The mathematical model was developed which accounts the change in feed characteristics and percent solids. The hardware required to control the Falcon bowl speed and underflow rate are being installed.

ABSTRACT

The application of dense medium and water-only Falcon concentrator has been evaluated for the recovery of carbon from the Pittsburgh No. 8 and Illinois No. 6 fine coal refuse ponds. The performance of the dense medium Falcon concentrator is close to washability data providing an organic efficiency in excess 95% for both coals. The pyritic sulfur in the Pittsburgh fine coal was reduced to 1.23% from 3.41% with a product yield of 73.43% having 8.52% ash. The dense medium Falcon produced a clean coal having 7.30% ash and with a product yield of 89.80% for Illinois No 6 fine coal refuse. The water-only Falcon while treating -48 mesh coal samples from both refuse ponds, produced a clean coal having ash contents of 8.51% and 7.76% with a product yield of 71.73% and 82% respectively for Pittsburgh No 8 and Illinois No 6 fine coal refuse. The pyritic sulfur contents were reduced to 0.95% and 0.15% from 2.40% and 0.51% respectively for Pittsburgh No. 8 and Illinois No. 6 fine coal refuse samples.

The Falcon concentrator was equally effective for treating refuse coal having different feed characteristics. Treatment of Jader refuse with water-only (-48 mesh) and dense medium Falcon (16 x 325 mesh) produced clean coal concentrates of 12.61% and 17.53% ash with a product yields of 42.30% and 35.76% from a coal having 41.30% and 48.64% ash. The concentrate of water-only Falcon contained 2.07% pyritic sulfur, which was reduced from 6.06% and the dense medium Falcon reduced the pyritic sulfur from 4.43% to 1.55%. Hence, the Falcon concentrator can be used in coal processing plants, where the variability of feed coal is quite common. The Falcon concentrator also effectively treated the tailings generated by the processing of refuse samples to produce pyritic and clay rich fractions for effective tailings management. The treatment of tailings of Pittsburgh No. 8 fine coal refuse produced a sulfur rich fraction and clay rich fraction having total sulfur contents of 13.35% and 3.54% respectively from a feed having a total sulfur content of 7.72%. The pyritic sulfur content in the mixed tailings was reduced to 2.76% from 5.73% with a total sulfur rejection of about 65%.

INTRODUCTION AND PROBLEM STATEMENT

Column flotation is effective in the recovery of ultrafine coal while producing low ash concentrates. However, like other the flotation processes, column flotation is not efficient for treating fine coal containing a significant amount of mixed-phase and free pyrite particles. It is a well-established fact that, theoretically, density-based processes provide a better separation of for mixed-phase and coal pyrite particles than surface-based processes (Adel et al 1991). Spirals are the most commonly used fine coal cleaning gravity concentration method, which has the following drawbacks:

- Low capacity (3 – 3.5 tons/hr) of each spiral start which necessitates distribution of feed to multiple units with a distributor and results in additional inefficiency due to inconsistent feed.
- Inability to provide low density cut points below 1.8 (Toney et al., 1998). Attempts to achieve low density cut points have resulted in high E_p values and loss of coarse coal.

The conventional gravity concentration methods are inefficient for treating fine coal due to the lack of a sufficient inertia force to allow acceptable settling kinetics of fine particles. Application of a centrifugal force to the conventional gravity concentration techniques has provided an effective solution to this problem and resulted in the development of many enhanced gravity concentrators (Luttrell et al., 1994; Riley and Firth, 1993; Venkatraman et al., 1995). These units have immediate application in the mineral industry but their application has been hindered by throughput capacity concerns and cost constraints in the coal processing industry.

The main aim if this task was to apply the enhanced gravity separation process to recover carbon from the refuse ponds and to remove harmful pyritic sulfur from the tailings stream, thereby creating a clay-rich fraction that can be utilized for land reclamation purposes. Neutralization of acid generating materials will become more economically viable by concentrating the pyritic sulfur in a small fraction of material.

GOALS AND OBJECTIVES

The goal of this study was to develop and demonstrate a enhanced gravity system which efficiently and economically recovers carbon from active or abandoned refuse ponds while simultaneously providing a remediation technique that will negate the environmentally harmful effects of waste disposal. The study focused on the treatment of high-sulfur, fine-coal refuse ponds, since these sources provide the ultimate challenge in terms of environmental remediation and cleaning to acceptable carbon qualities. To achieve this goal, two processing schemes utilizing state-of-the-art fine particle processing technologies were evaluated. The first scheme utilized a dense-medium application to an enhanced-gravity concentrator commercially known as the Falcon concentrator and the second process represented a water-only circuit that may prove to be desirable for the treatment of waste in which the carbon is easy to recover at the desirable grade. The water-only circuit involves the use of a novel hindered-bed concentrator that has been recently designed by Eriez Magnetic to apply air assistance to recover the coarse

carbon particles. After the initial rejection of coarse ash-bearing material by the Eriez separator, the clean coarse carbon (16 x 48 mesh) was recovered from the overflow of a screen while enhanced-gravity concentration was applied to -48-mesh fraction to clean and recover the fine carbon.

The scope of this task was to accomplish the following objectives:

- Determine the effects of operating and design variables of the Falcon concentrator on its performance.
- Development and validation of mathematical models for dense medium and water-only Falcon concentrator to relate its process variables and performance.
- Optimization and validation of the dense medium and water-only Falcon experiments.
- Development of an algorithm using the model to control the water-only Falcon for varying operating conditions.
- Testing of control strategy on the C-10 dense medium falcon concentrator using online AMDEL coal analyzer.

OVERALL APPROACH

The main aim of this task was to develop an efficient, environmentally friendly system for the economical recovery of carbon from fine-coal refuse ponds. The two carbon recovery systems were evaluated and compared based on technical and economical factors. The first circuit involved a dense-medium application to an enhanced-gravity separator commercially known as the Falcon Concentrator. The feed slurry from the refuse pond was subjected to desliming using a classifying cyclone circuit (Figure 4.1). The deslimed material (16 x 325 mesh) was subjected to dense-medium separation in the Falcon Concentrator. The magnetite used in this study was 100% passing -325 mesh, to facilitate the separation process. The magnetite in the product and tailing streams of the Falcon unit were recovered in a magnetite recovery circuit using Eriez magnetic separators.

A water-only based circuit, as shown in Figure 4.2, was also tested in this task. While this circuit may have a lower capital cost, it was expected that the separation efficiencies will be lower than the circuit shown in Figure 1 but more efficient than traditional circuits. These circuits typically utilize spiral concentrators and column or conventional flotation to recover the carbon from refuse ponds. In the water-only circuit, the feed slurry was fed directly to a hindered-bed gravity separator developed by Eriez Magnetics, which provides air-assistance to recover the coarse coal particles. The purpose of the hindered-bed separator was to reject the coarsest ash-bearing particles. The overflow of the separator was passed across a 48-mesh screen to remove a coarse clean carbon product. The selection of the 48-mesh screen was based on a previous study conducted at SIUC. The underflow of the 48-mesh screen was then treated by a water-only Falcon operation followed by subsequent treatment of the product by the novel ISGS/Jameson Cell flotation device in a rougher-cleaner arrangement. This arrangement has been found in a recent SIUC project funded by the Illinois Clean Coal Institute to provide the most

efficient water-only separation performance. The product and tailing streams are treated in the same manner as described in the dense-medium based circuit in Figure 4.1.

Conducting experiments as per Plackett-Burman design based on a statistical approach identified the important variables of the dense medium Falcon. The detailed experiments were based on the Box-Benken design to develop mathematical models for dense and water-only Falcon processes. The Design Expert software was used to develop and analyze the data generated by the test program. Experiments were carried out varying feed ash, percent solids, underflow rate and bowl speed to develop a mathematical model for automation of the Falcon concentrator. The model was used to control the Falcon to obtain the required grade and yield of clean coal with change in feed characteristics.

Figure 4.1 The dense-medium enhanced gravity carbon recovery system.

Figure 4.2. The water-only enhanced gravity concentration carbon recovery circuit.

RESULTS AND DISCUSSIONS

In the enhanced gravity concentration task, the important operating variables of the Falcon Concentrator will be identified and its performance will be studied while treating two coals having different feed characteristics. To accomplish this goal, Plackett-Burman and Box-Behnken statistical designs will be applied to identify and optimize the important variables.

The coal samples from refuse ponds of Illinois No. 6 coal and Pittsburgh No 8. coal fines were used for the present study.

Dense Medium Falcon Process (Plackett-Burman design)

A statistically designed set of experiments using Plackett-Burman design (Table 4.1) was conducted on the dense medium Falcon to identify the most significant operating variables. The variables and their respective value range used for the statistical design were:

Bowl speed (20 to 40 Hz)
 Feed flow rate (45 to 182 lpm)
 Feed medium density (1.3 to 1.5)
 Feed solids content (5% to 15% by weight)
 Underflow rate (5 to 10 lpm)
 Lip width (1.27 to 3.81 cm).

It was proposed in the Project Management report to conduct a total of 8 tests based on the Plackett-Burman design. However, analysis of the design revealed that the Design-Expert calculates alias patterns for all Plackett-Burman designs. For example, the air pressure setting needed to provide a given underflow rate was found to be a function of bowl speed and feed solids concentration. Alias structures for the 8 run designs are complex, because each main effect is partially confounded with several two-factor interactions as given below:

$$\begin{aligned}
 [\text{Intercept}] &= \text{Intercept} + \text{ABD} + \text{ACE} + \text{BCF} + \text{DEF} \\
 [A] &= A + \text{BD} + \text{CE} + \text{BEF} + \text{CDF} \\
 [B] &= B + \text{AD} + \text{CF} + \text{AEF} + \text{CDE} \\
 [C] &= C + \text{AE} + \text{BF} + \text{ADF} + \text{BDE} \\
 [D] &= D + \text{AB} + \text{EF} + \text{ACF} + \text{BCE} \\
 [E] &= E + \text{AC} + \text{DF} + \text{ABF} + \text{BCD} \\
 [F] &= F + \text{BC} + \text{DE} + \text{ABE} + \text{ACD} \\
 [AF] &= AF + BE + CD + ABC + ADE + BDF + CEF
 \end{aligned}$$

where in A, B, C, D, E and F are the factors. Since the main factors are confounded with 2 and 3 factor interactions, the Plackett-Burman design based on 8 experiments may not identify the important parameters if the two factor interactions are significant. Therefore, it was decided to conduct a Plackett-Burman design based on 16 experiments. Alias patterns of the Design-Expert for 16 experiments were determined as:

$$\begin{aligned}
 [\text{Intercept}] &= \text{Intercept} \\
 [A] &= A + \text{BCE} + \text{DEF} \\
 [B] &= B + \text{ACE} + \text{CDF} \\
 [C] &= C + \text{ABE} + \text{BDF} \\
 [D] &= D + \text{AEF} + \text{BCF} \\
 [E] &= E + \text{ABC} + \text{ADF} \\
 [F] &= F + \text{ADE} + \text{BCD} \\
 [AB] &= AB + \text{CE} \\
 [AC] &= AC + \text{BE}
 \end{aligned}$$

[AD]	=	AD	+	EF					
[AE]	=	AE	+	BC	+	DF			
[AF]	=	AF	+	DE					
[BD]	=	BD	+	CF					
[BF]	=	BF	+	CD					
[ABD]	=	ABD	+	ACF	+	BEF	+	CDE	
[ABF]	=	ABF	+	ACD	+	BDE	+	CEF	

The alias patterns show that the main effects are confounded only with three factor interactions. It can be safely assumed that the effect of the three factor interactions may be negligible compared to two factor interactions. The Plackett-Burman design based on 16 experiments is given in Table 4.1.

Table 4.1. Randomized Plackett-Burman experimental program used to identify operating parameters having a significant impact on separation performance.

Run No.	Speed (Hz)	Underflow Rate (lpm)	Relative Medium Density	Feed Rate (lpm)	Feed solids (% by wt.)	Lip width (cm)
1	20	10	1.3	182	15	1.27
2	40	10	1.3	45	5	3.81
3	20	10	1.5	45	5	1.27
4	40	3	1.5	182	5	1.27
5	40	10	1.5	45	15	1.27
6	20	10	1.3	45	15	3.81
7	20	3	1.5	45	15	3.81
8	20	10	1.5	182	5	3.81
9	40	3	1.5	45	5	3.81
10	20	3	1.3	182	5	3.81
11	20	3	1.3	45	5	1.27
12	40	10	1.5	182	15	3.81
13	40	3	1.3	182	15	3.81
14	20	3	1.5	182	15	1.27
15	40	3	1.3	45	15	1.27
16	40	10	1.3	182	5	1.27

Falcon Experiments

The experiments involving the dense medium application to the Falcon Concentrator were conducted using a 25-cm diameter bowl having an angle of 14° from vertical. A schematic diagram of the experimental setup is given in Figure 4.3. The feed coal to the Falcon (16 x 325 mesh) was prepared by screening and classifying the coal sample. Prior to each test, the feed sump was filled with a measured quantity of water and coal sample to achieve the required feed pulp density. A pre-calculated amount of magnetite (99%

passing -45 microns of 99.9% purity) was then added to the feed sump to obtain the required medium density. The slurry in the feed sump was kept in suspension using stirrers and a re-circulation circuit. After measuring the feed pulp density, the desired feed flow rate was set by adjusting the by-pass valve. The required operating levels of the Falcon concentrator, such as the bowl speed and underflow rate were set. The feed, concentrate and tailing samples were collected after allowing sufficient time for attaining steady-state conditions. The samples collected will be subjected to screening over a 325-mesh screen to separate the coal and magnetite. The remaining magnetite in the sample was removed using a hand magnet. The samples were filtered, dried, weighed and further analyzed for ash and total sulfur contents using ASTM procedures.

Figure 4.3 Schematic diagram of the experimental setup used for the dense medium Falcon tests.

Analysis of data

Empirical models describing the product ash, yield and total sulfur rejection (TS rejection) as a function of the operating parameter values were derived in quadratic form.

$$\begin{aligned} \text{Product Ash} &= 8.86875 + 0.93125 \times A - 0.732 \times B + 0.54875 \times C + 0.465 \times D - 0.4725 \times E \\ &\quad - 0.35375 \times F + 0.5125 \times A \times B \times F \end{aligned} \quad [4.1]$$

$$\text{Yield} = 69.5139 - 5.10066 \times A - 8.76415 \times B + 12.3069 \times C + 7.78039 \times D + 2.84268 \times F -$$

$$5.97825 \times A \times C + 8.82667 \times A \times E + 6.8631 \times A \times F + 6.64353 \times B \times D \quad [4.2]$$

$$\text{TS Rejection} = 41.617 - 7.866 \times A + 4.69552 \times B + 9.26611 \times C - 7.73674 \times E - 6.63247 \times F + 5.73208 \times A \times F - 3.35347 \times B \times D + 5.84276 \times B \times F + 8.80089 \times A \times B \times F \quad [4.3]$$

in which A is the bowl speed (Hz), B the under flow rate (lpm), C the medium density (gm/cm^3), D the feed rate (lpm), E the feed solids content (% by weight), F the lip width (cm). The equations are presented in coded form in which a value ranges of -1 to 1 represents each parameter.

Equations 4.2 and 4.3 show that the responses are dependent on two factor interactions. Hence, the Plackett-Burman design based on 8 tests may not have revealed the true significance of main interactions. The actual and predicted values for product ash, yield and total sulfur rejection using Equations 4.1 to 4.3 are given in Figure 4.4. These figures suggest that the Eqs. [4.1] – [4.3] can be used for further analysis of the results.

The coefficients of Eqs. [4.1] to [4.3] and their significance are provided in Tables 4.2 - 4.4. The associated p -values ("Prob > |t|") are interpreted as the probability of realizing a coefficient as large as that observed, when the true coefficient equals zero. In other words, small values of p (less than 0.05) indicate significant coefficients in the model. The variance inflation factor (VIF) measures how much the variance of the model is inflated by the lack of orthogonality in the design. If the factor is orthogonal to all the other factors in the model, the VIF is 1.0. Table 4.2 shows that, for product ash content, the important parameters are bowl speed, underflow rate and medium density while sulfur rejection depends on feed solids content and lip width in addition to the aforementioned parameters. Only two parameters were found to significantly effect the product mass yield, i.e., underflow rate and medium density. The significance of each parameter on product ash, yield and total sulfur rejection are pictorially depicted using perturbation plots (Figure 4.5). It can be concluded that medium density, underflow rate and bowl speed significantly affect all three responses.

It is interesting to note that feed solids concentration does not have a negative effect on product ash and mass yield based on a 95% significance level (Figure 4.5(a)). In fact, increasing the feed solids over the range 5% to 15% by weight resulted in a decrease in product ash content without affecting mass yield. However, it is expected that further increases in the feed solids content would eventually results in a higher recovery of high-ash content particles to the product stream and, as a result, elevated mass yields.

Another finding of interest was that excellent performances were achieved at relatively high feed solid contents up to 15% by weight indicates that the process is not significantly impacted by the magnetite-to-coal ratio. This fact differs from typical operating conditions employed for dense-medium cyclones. Hence, for the present study, a feed solids concentration of 15% was established for all subsequent experiments in this investigation.

Figure 4.4. A comparison of the predicted response variable values obtained using the empirical models for (a) product ash content (b) product mass yield and (c) total sulfur rejection and those obtained from actual tests using the Illinois No. 6 refuse material (16 x 325 mesh).

Table 4.2. Least square coefficients of the model equation for ash with a test of their significance.

Factor	Coefficient	Prob > t	VIF
Intercept	8.86875		
A - Speed	0.93125	0.0037	1
B - U/F rate	-0.7325	0.0129	1
C- M. Density	0.54875	0.0442	1
D-Feed rate	0.465	0.0779	1
E- Feed solids	-0.4725	0.0741	1
F -Lip width	-0.35375	0.1627	1
ABF	0.5125	0.0565	1

Table 4.3. Least square coefficients of the model equation for product yield with a test of their significance.

Factor	Coefficient	Prob > t	VIF
Intercept	69.5139		
A-Speed	-5.10066	0.2006	1
B-U/F rate	-8.76415	0.0484	1
C-M. Density	12.3069	0.0133	1
D-Feed rate	7.78039	0.0708	1
F-Lip width	2.84268	0.4535	1
AC	-5.97825	0.1430	1
AE	8.82667	0.0473	1
AF	6.8631	0.1012	1
BD	6.64353	0.1103	1

Table 4.4. Least square coefficients of the model equation for total sulfur rejection with a test of their significance.

Factor	Coefficient	Prob > t	VIF
Intercept	41.617		
A-Speed	-7.866	0.0033	1
B-U/F rate	4.69552	0.0309	1
C-M. Density	9.26611	0.0015	1
E-Feed solids	-7.73674	0.0036	1
F-Lip width	-6.63247	0.0074	1
AF	5.73208	0.0140	1
BD	-3.35347	0.0918	1
BF	5.84276	0.0129	1
ABF	8.80089	0.0019	1

Figures 4.5 (a) and (c) show that volumetric feed flow rate has the least impact on product ash content and mass yield while providing virtually no effect on total sulfur rejection. The dense-medium process provides a situation that clearly defines the direction in which the light and heavy particles will travel in the system. However, the rate at which the particles travel is dependent on the relative difference between the particle density and the medium density. Therefore, it is expected that volumetric feed rate will affect the efficiency of treating the near-gravity material through the alteration of particle retention time. However, results from the test program and those from a previous investigation indicate that a volumetric feed flow rate of 138 lpm can be used without significantly impacting the separation performance.

The lip width ultimately controls the thickness of the particle bed formed around the circumference of the bowl wall. The parameter was found to provide a significant impact on product ash and total sulfur contents as well as mass yield. In general, an increase in the lip width improved process performance. This may be due to the fact that an increase in lip width may enhance particle stratification of the bed.

Dense Medium Falcon Process (Box-Behnken design)

Illinois No. 6 fine coal refuse

Statistically designed experiments were carried out according to a Box-Behnken design to provide data for developing more accurate models to quantify parameter effects and determine their respective optimum values over a range of product qualities. The following parameters were used for the experimental campaign:

Bowl speed (10, 20, 30 Hz);
Underflow rate (5, 7.5, 10 lpm);
Medium Density (1.3, 1.4, 1.5 gm/cm³);
Lip width (1.27, 3.81, 6.35 cm)

It should be noted that the maximum bowl speed used in these tests was 30Hz, as compared to the 40Hz used in the Plackett-Burman tests. The bowl speed was reduced due to noticeable destabilization of the dense medium at the high bowl speeds. A total number of 29 experiments were performed using the Box-Behnken design. The samples collected from each experiment were wet screened through a 325-mesh sieve to separate the magnetite. A hand magnet removed the remaining magnetite. The +325 fractions were dried and analyzed for ash and total sulfur contents. The experimental conditions and responses are provided in Table 4.5.

The data were analyzed using the Design Expert software. Cubic and quadratic models were fitted to the data to understand the significance of each parameter and their interactions. The model equations relating the parameters and their interactions for responses product ash (%), product yield (%) and total sulfur rejection can be written in reduced form as:

(a)

(b)

(c)

Figure 4.5 Perturbation plots showing the parameter effects on (a) product ash, (b) product mass yield and (c) total sulfur rejection; Illinois No. 6 refuse material.

$$\begin{aligned} \text{Product Ash (\%)} = & 8.6753 - 0.5921 \times A - 0.2468 \times B - 0.1665 \times C - 0.1823 \times D - 0.5591 \times \\ & C^2 + 0.3460 \times A \times B - 0.4169 \times A \times D + 0.6219 \times A^2 \times B - 0.8230 \times A^2 \times D + 0.4181 \times A \times C^2 - \\ & 0.9173 \times B^2 \times C - 0.7279 \times B \times D \end{aligned} \quad [4.4]$$

$$\begin{aligned} \text{Product Yield (\%)} = & 90.1428 + 3.9583 \times A - 3.3612 \times B + 6.0406 \times C - 0.8182 \times D - 3.4635 \times A^2 \\ & - 4.8080 \times C^2 + 4.9240 \times A \times B - 2.9121 \times A \times D + 4.2465 \times B \times C \end{aligned} \quad [4.5]$$

$$\begin{aligned} \text{TS Rejection (\%)} = & 28.4613 - 2.1087 \times A + 2.7925 \times B - 5.0715 \times C + 3.9465 \times D + \\ & 4.3239 \times C^2 - 7.0478 \times A \times B + 2.4337 \times A \times D - 4.1437 \times B \times C \end{aligned} \quad [4.6]$$

in which A is the bowl speed (Hz), B the under flow rate (lpm), C the medium density (gm/cm^3), D the lip width (cm).

The predicted and actual responses for product ash, yield and total sulfur rejection are shown in Figure 4.6. The effects of the operating parameters on each response variable are summarized in the perturbation plots (Figures 4.7, 4.9 and 4.11). As shown, bowl speed and medium density have the greatest effect on product ash content. An increase in bowl speed decreases the product ash content, which is likely due to the increase in particle settling kinetics. The curvilinear nature of the product ash curve suggests that the product ash is a strong quadratic function of medium density, which is supported by a relatively low t -statistic obtained for C^2 term. Figure 4.8 shows that, at a low bowl speed, the effect of medium density on product ash is nonlinear, while at high bowl speeds, the effect is minimal. This finding may be due to a higher degree of stratification of the magnetite particles while applying relatively high centrifugal forces. As such, the high-ash particles may not be able to pass through the high-density bands, which minimizes the impact of the initial medium density on product ash content. For the same reason, mass yield was not significantly effected by the high medium densities at elevated bowl speeds (Figure 4.10). At a 1.45 medium density and at a bowl speed of 30 Hz, the product yield was nearly 93%, which was not significantly increased by raising the medium density above 1.4.

The function of lip in the Falcon has been previously discussed. A larger lip in the Falcon increases the thickness of the particle bed, thereby, improving particle stratification and thus the separation performance. The perturbation plots (Figure 4.7, 4.9 and 4.11) provide further evidence that a wider lip improves the overall separation efficiency by decreasing mass yield while reducing both the product ash and total sulfur contents. Figure 4.12 further depicts the lip width effect on total sulfur rejection and the corresponding interactive relationship with medium density.

Table 4.5. The test design matrix and responses for the Box-Behnken test program conducted on the dense-medium Falcon process using the Illinois No. 6 coal refuse material; feed ash $\approx$ 14%.

Run No.	Speed (Hz.) A	Underflow Rate (lpm) B	Medium Density C	Lip width (cm) D	Product Ash (%)	Product Yield (%)	Total Sulfur Rejection (%)
1	20	7.5	1.4	3.81	8.92	91.62	25.74
2	30	7.5	1.4	6.35	6.80	85.41	34.48
3	30	7.5	1.5	3.81	7.78	90.99	27.09
4	10	7.5	1.4	6.35	8.84	81.11	34.51
5	10	5.0	1.4	3.81	9.25	91.55	22.67
6	10	10.0	1.4	3.81	9.30	73.83	40.16
7	30	5.0	1.4	3.81	7.39	90.63	31.32
8	10	7.5	1.3	3.81	8.36	75.72	41.69
9	30	7.5	1.3	3.81	8.29	81.89	37.44
10	20	10.0	1.5	3.81	7.03	89.55	30.47
11	20	10.0	1.3	3.81	8.80	66.68	47.19
12	10	7.5	1.5	3.81	8.41	87.78	27.49
13	10	7.5	1.4	6.35	10.02	76.72	30.90
14	20	7.5	1.5	1.27	7.95	91.42	22.21
15	20	10.0	1.4	6.35	7.73	88.61	30.10
16	30	7.5	1.4	1.27	9.64	92.67	21.14
17	20	5.0	1.4	1.27	9.97	93.67	19.71
18	20	7.5	1.3	6.35	8.02	79.06	40.09
19	20	7.5	1.4	3.81	8.20	91.27	31.69
20	20	7.5	1.4	3.81	8.10	90.92	30.83
21	20	5.0	1.3	3.81	9.76	84.81	28.89
22	20	5.0	1.5	3.81	7.19	90.69	28.74
23	30	10.0	1.4	3.81	8.84	92.61	20.62
24	20	10.0	1.4	1.27	9.36	89.95	26.25
25	20	7.5	1.4	3.81	8.49	91.69	27.39
26	20	5.0	1.4	6.35	7.96	90.22	29.95
27	20	7.5	1.5	6.35	7.51	90.89	30.28
28	20	7.5	1.4	3.81	8.68	92.22	26.40
29	20	7.5	1.3	1.27	8.31	80.68	31.84

Figure 4.6. A comparison of the predicted response variables obtained from the empirical models (Eqs. [4.4]-[4.6] for (a) product ash, $R^2=0.94$, (b) mass yield, $R^2=0.89$ and (c) total sulfur rejection, $R^2=0.89$ and the actual values from the Box-Behnken tests conducted on the Illinois No. 6 refuse material; feed ash $\approx 14\%$.

Figure 4.7. Perturbation plot showing the effect of the operating parameter values on product ash response, Illinois No. 6 refuse material.

Figure 4.8. The interactive effect of bowl speed and medium density values on the product ash response, Illinois No. 6 refuse material.

Figure 4.9. Perturbation plot showing the effect of the operating parameter values on product mass yield, Illinois No. 6 refuse material.

Figure 4.10. The interactive effect of bowl speed and medium density values on the product mass yield response, Illinois No. 6 refuse material.

Figure 4.11. Perturbation plot showing the effect of the operating parameter values on total sulfur rejection, Illinois No. 6 refuse material.

Figure 4.12. The interactive effect of lip width and medium density values on total sulfur rejection, Illinois No. 6 refuse material.

The metallurgical results obtained from the Box-Behnken tests are compared with the theoretical mass yield versus product ash curve in Figure 4.13. These results show that it is possible to obtain a clean coal product containing approximately 6.8% ash and 2.47% total sulfur from the treatment of the 16 x 325 mesh particle size fraction in the Illinois No. 6 refuse material. Approximately 85% of the feed mass was recovered to the product, which represents 95% of the theoretically attainable yield or a 95% organic efficiency. In fact, organic efficiency values greater than 95% were realized from many of the tests.

Figure 4.13. Metallurgical performance of the dense medium Falcon obtained on the basis of product ash from the treatment of 16 x 325 mesh particle size fraction of the Illinois No. 6 fine coal refuse; feed ash and total sulfur = 13.8% and 3.22%, respectively.

Pittsburgh No. 8 fine coal refuse

Statistically designed experiments were also conducted on the treatment of the Pittsburgh No. 8 refuse material using the dense-medium application to the Falcon Concentrator. A Box-Behnken experimental program investigated the effects of the following parameters and associated parameter values ranges on separation performance:

Bowl speed (10, 20, 30 Hz);
 Underflow rate (5, 10, 15 lpm);
 Medium Density (1.2, 1.35, 1.5 gm/cm³);
 Lip width (1.27, 3.81, 6.35 cm).

The upper level of underflow rate was increased to 15 lpm while the lower level of medium density value was reduced to 1.2 gm/cm³ to improve the potential of achieving lower product ash contents than those realized in the test program conducted on the Illinois No. 6 material. A total number of 29 experiments were carried out in accordance to the Box-Behnken design. The samples collected from each experiment were wet screened through a 325-mesh screen to separate the magnetite. A hand magnet removed the remaining magnetite. The +325 fractions were dried and analyzed for ash and total sulfur contents. The experimental conditions and responses are provided in Table 4.6.

The data were analyzed using the Design Expert software. A quadratic model was fitted to the data to understand the significance of each parameter and their interactions. The model equations relating the parameters and their interactions to the product ash content, mass yield and total sulfur rejection can be written in reduced form as follows:

$$\begin{aligned} \text{Product Ash (\%)} = & 8.072 - 2.395 \times A - 1.7275 \times B + 2.36667 \times C \\ & - 0.0591667 \times D + 4.16108 \times A^2 + 2.21233 \times B^2 + 1.51608 \times C^2 + 1.95233 \times D^2 + \\ & 1.2975 \times B \times D - 1.0825 \times C \times D \end{aligned} \quad [4.7]$$

$$\begin{aligned} \text{Product Yield (\%)} = & 69.1871 - 2.46095 \times A - 6.07213 \times B + 25.6222 \times C + \\ & 1.21715 \times D + 8.45314 \times A^2 - 10.5084 \times C^2 - 8.85846 \times B \times D \end{aligned} \quad [4.8]$$

$$\begin{aligned} \text{TS rejection} = & 69.2829 + (8.13085 \times A) + (7.42892 \times B) - (19.5531 \times C) - \\ & (0.714765 \times D) - (16.3111 \times A^2) - (6.70456 \times B^2) - (5.16715 \times D^2) \end{aligned} \quad [4.9]$$

The actual and predicted values using Eqs. [4.7], [4.8], and [4.9] are compared in Figures 4.14(a), (b) and (c). A statistical evaluation of the parameter and parameter interaction coefficients is also provided in Tables 4.7, 4.8 and 4.9. Table 4.7 shows that speed, underflow rate and medium density significantly affect the product ash, as indicated by their low t-statistic values. The lip width does not have much effect on product ash. The significance of the variables is revealed by very low t-statistic values for speed, underflow rate and lip width and their quadratic nature are pictorially depicted in Figure 4.15. It is evident from the perturbation plot in Figure 4.15 that the two parameters have the greatest impact on product ash content are medium density and speed. The interactive affects of medium density and speed, and underflow rate and speed are illustrated in Figures 4.16 and 4.17 respectively. As expected, an increase in medium density results in a relatively sharp decline in product quality (Fig 4.16). The same affect is observed by decreasing the bowl speed below 20 hz, which is likely due to a drop in the settling kinetics of the high-ash content, near gravity particles. Similarly, as observed in the treatment of the Illinois No. 6 material, an increase in bowl speed from 20 to 30 hz resulted in decrease in product ash content, although the change is less significant. As discussed previously, this may be due to destabilization of the magnetite suspension with an increase in bowl speed.

The effects of lip width and underflow rate are shown in Figure 4.18. The lower lip width and underflow rate significantly increases the product ash. As explained earlier, lower lip

width reduced the possibility of forming a stable bed. The product ash drastically reduces from 18.56% to 7.39% at a higher lip width and underflow rate.

Table 4.6. The test design matrix and responses from the Box-Behnken test program conducted on the Pittsburgh No. 8 refuse coal, feed ash $\approx$ 22%.

Run No.	Speed (Hz.) A	Underflow Rate (lpm) B	Medium Density C	Lip Width (cm) D	Product Ash (%)	Product Yield (%)	Total Sulfur Rejection (%)
1	20	10	1.35	3.81	7.35	67.27	69.04
2	30	10	1.35	6.35	9.61	75.55	60.10
3	30	10	1.50	3.81	11.85	83.87	52.94
4	10	10	1.35	6.35	17.37	83.36	35.90
5	10	5	1.35	3.81	19.32	92.86	20.12
6	10	15	1.35	3.81	15.84	59.19	54.83
7	30	5	1.35	3.81	16.27	86.56	32.60
8	10	10	1.20	3.81	13.38	51.14	65.94
9	30	10	1.20	3.81	10.67	30.88	83.27
10	20	15	1.50	3.81	14.28	85.19	42.77
11	20	15	1.20	3.81	7.94	20.64	90.58
12	10	10	1.50	3.81	16.76	87.91	34.79
13	10	10	1.35	1.27	16.46	85.13	33.72
14	20	10	1.50	1.27	14.98	87.47	44.29
15	20	15	1.35	6.35	8.96	64.80	67.41
16	30	10	1.35	1.27	11.71	79.25	54.61
17	20	5	1.35	1.27	16.94	49.49	61.75
18	20	10	1.20	6.35	12.23	27.67	83.61
19	20	10	1.35	3.81	7.44	67.12	68.85
20	20	10	1.35	3.81	8.56	64.54	60.09
21	20	5	1.20	3.81	8.87	51.07	75.01
22	20	5	1.50	3.81	14.52	88.25	43.28
23	30	15	1.35	3.81	10.28	73.95	59.36
24	20	15	1.35	1.27	9.30	70.66	62.13
25	20	10	1.35	3.81	7.27	69.86	68.40
26	20	5	1.35	6.35	11.41	79.06	55.17
27	20	10	1.50	6.35	15.99	90.02	32.18
28	20	10	1.35	3.81	7.02	64.54	71.80
29	20	10	1.20	1.27	6.89	33.86	86.46

(a)

(b)

(c)

Figure 4.14. Comparisons of the predicted response variables obtained from the empirical models (Eq. [4.7], [4.8] and [4.9]) for (a) product ash content, $R^2=0.81$, (b) product yield, $R^2=0.88$ and (c) TS rejection, $R^2=0.86$ and those obtained from the actual experiments conducted on the Pittsburgh No. 8 fine coal refuse; feed ash $\approx 22\%$.

Table 4.7. Least square coefficients of the model equation for product ash content with a test of their significance; Pittsburgh No. 8 refuse material.

Factor	Coefficient	Prob > t	VIF
Intercept	8.072		
A-Speed	-2.395	0.0007	1
B-U/F rate	-1.7275	0.0085	1
C-M. Density	2.36667	0.0008	1
D-Lip width	-0.05917	0.9205	1
A ²	4.16108	< 0.0001	1
B ²	2.21233	0.0123	1
C ²	1.51608	0.0726	1
D ²	1.95233	0.0245	1
BD	1.2975	0.2162	1
CD	-1.0825	0.2991	1

Table 4.8. Least square coefficients of the model equation for yield with a test of their significance; Pittsburgh No. 8 refuse material.

Factor	Coefficient	Prob > t	VIF
Intercept	69.1871		
A-Speed	-2.46095	0.3018	1
B-U/F rate	-6.07213	0.0163	1
C-M. Density	25.6222	< 0.0001	1
D-Lip width	1.21715	0.6061	1
A ²	8.45314	0.0118	1
C ²	-10.5084	0.0025	1
BD	-8.85846	0.0391	1

Table 4.9. Least square coefficients of the model equation for total sulfur rejection with tests of their significance.

Factor	Coefficient	Prob > t	VIF
Intercept	69.2829		
A - Speed	8.13085	0.0015	1
B - U/F rate	7.42892	0.0032	1
C - M. Density	-19.5531	< 0.0001	1
D - Lip width	-0.71477	0.7518	1
A ²	-16.3111	< 0.0001	1
B ²	-6.70456	0.0353	1
D ²	-5.16715	0.0975	1

Treatment of the Pittsburgh No. 8 refuse material under the given operating conditions revealed that mass yield is mainly a function of medium density, which is depicted in Figures 4.19 and 4.20. The expected trend of increasing mass yield with a corresponding rise in medium density was observed. The other operating parameters appeared to have a relatively minor impact over the range of values tested.

It is evident from the perturbation plot in Figure 4.21 that the three parameters that have the greatest impact on total sulfur rejection are medium density, bowl speed and underflow rate. As expected, an increase in medium density results in a relatively sharp decline in total sulfur rejection. The same trend is observed by decreasing the bowl speed below 20 Hz, which is likely due to a drop in the settling kinetics of the pyrite particles. Any increase in the underflow rate removes higher amount of the tailings fraction, thus improving the grade of the product. However, the maximum underflow rate that can be maintained depends on the rate of settling of the heavier fraction to be able to maintain a stable bed inside the Falcon Concentrator. Hence, an increase in the underflow rate initially increases the total sulfur rejection and a very high underflow rate is detrimental to the total sulfur rejection.

The interactive effects of bowl speed and medium density, and underflow rate and bowl speed are illustrated in Figures 4.22 and 4.23. An increase in medium density sharply decreases the total sulfur rejection. Whereas, a higher bowl speed increases the total sulfur rejection due to increased settling rate of particles (Fig. 4.22). The quadratic nature of underflow rate and bowl speed relationships for total sulfur rejection is shown in Figure 4.23.

Figure 4.15 Perturbation plot showing the effect of different parameters on the product ash response content; Pittsburgh No. 8 refuse material.

Figure 4.17 Plot illustrating the effect of bowl speed and underflow rate on product ash response, Pittsburgh No. 8 coal

Figure 4.16 Plot illustrating the effect of bowl speed and medium density on product ash response, Pittsburgh No. 8 coal

Figure 4.18. Plot illustrating the effect of underflow rate and lip width on product ash response, Pittsburgh No. 8 coal.

Figure 4.19. Perturbation plot showing the effect of different parameters on product yield response, Pittsburgh No. 8 coal.

Figure 4.20. Plot illustrating the effect of bowl speed and medium density on product yield response, Pittsburgh No. 8 coal.

Figure 4.21. Perturbation plots showing the parameter effects on total sulfur rejection (Pittsburgh No. 8 fine coal refuse)

Figure 4.23 The response surface showing the effects of underflow rate and bowl speed on the total sulfur rejection, Pittsburgh No. 8 fine coal refuse.

Figure 4.22 The response surface showing the effects of bowl speed and medium density on the total sulfur rejection, Pittsburgh No. 8 fine coal refuse.

Process Optimization

The model equations developed using a statistical Box-Behnken experimental design methodology were used to optimize the dense medium Falcon performance for achieving optimum separation performance. A steepest ascent/descent optimization routine was utilized to maximize/minimize the desirable merit function for simultaneous optimization of multiple responses. The goal was to minimize the product ash and maximize the product yield. By changing the criteria used to achieve the goal, it was possible to obtain conditions for factors under which minimum product ash could be obtained for a particular target product mass yield. These conditions are tabulated in Table 4.10 and 4.11. The analysis of Box-Behnken design revealed that the lip width fails to significantly influence the product ash content and mass yield. Also, for amenability of the Falcon Concentrator for process control, it is easier to vary the other parameters than lip width. Hence, during optimization, emphasis was given to optimize the responses keeping the lip width constant.

The optimum conditions for a range of product ash and mass yield values achieved from the treatment of Pittsburgh No. 8 and Illinois No. 6 coals are provided in Tables 4.10 and 4.11, respectively. For the Pittsburgh No. 8 coal, the model tries to control the medium density for a given product ash and yield. At a very high product ash and yield the model also tries to increase the bowl speed and decrease the underflow rate (Table 4.10). For Illinois No. 6 coal, the model attempts to adjust the bowl speed and lip width to achieve the specified targets.

Table 4.10 Optimized factor levels to be maintained in order to achieve target separation performance (Pittsburgh No. 8 refuse coal)

Run No.	Factor				Predicted Product Ash (%)	Predicted Product Yield (%)
	A	B	C	D		
1	23.08	11.10	1.35	1.00	7.00	67.85
2	23.36	10.56	1.40	1.00	7.99	74.95
3	24.83	10.21	1.43	1.00	9.00	79.41
4	27.87	9.41	1.45	1.00	11.00	85.42
5	22.17	6.47	1.48	1.00	12.99	87.15
6	30.00	8.37	1.50	1.00	14.54	92.74

Table 4.11. Optimized factor levels to be maintained in order to achieve target separation performance (Illinois No. 6 refuse coal)

Run No.	Factor				Predicted Product Ash	Predicted Product Yield
	A	B	C	D	(%)	(%)
1	30.00	5.00	1.42	1.27	6.00	87.20
2	30.00	5.00	1.40	1.08	7.00	88.45
3	26.84	5.00	1.40	1.00	7.98	91.22
4	19.44	5.00	1.40	1.00	8.97	93.54
5	18.66	5.00	1.40	1.00	9.53	93.56

Experiments were carried out with the Pittsburgh No. 8 and Illinois No. 6 refuse fine coals, under these optimum conditions to validate the model predictions. Figures 4.24 (a) and (b) show graphically the comparison of the optimized performance and washability data. Experimental results indicate that a clean coal product containing 8.53% ash with 73.43% product yield was achieved from the dense medium Falcon process treating the Pittsburgh No. 8 refuse coal sample having a feed ash content of 22.0%. The organic efficiency (=actual recovery/theoretical recovery) achieved was 96%. The total sulfur content was reduced from 5.15% to 2.41%. The pyritic sulfur content was reduced from 3.41% to 1.23%. As also observed from the tests involving the Illinois No. 6 refuse coal, very high organic efficiency values in excess of 95% were realized, which produced clean coal concentrate containing 7.25% ash and 2.39% total sulfur with a product yield of 89.80% from a feed coal having 14.23% ash and 3.43% total sulfur. The pyritic sulfur content was reduced from 0.53% to 0.28%.

The major objective of using dense medium separation is to minimize the particle size effect and try to achieve a separation based on the density. Hence, to find out the particle size dependence on the separation process of the Falcon, the concentrate and tailings samples were subjected to particle size-by-size analyses on the basis of weight and ash content. The classification plots based on the fractions of feed and feed ash reporting to concentrate are plotted in Figure 4.25. Within the particle size range of 150 to 600 micrometers, the percent of feed reporting to concentrate varies from 72% to 81%. Whereas, at a particle size of 74 microns, about 67% of the feed reports to concentrate. However, at a size of 44 micrometers, only 50% of the feed reports to concentrate. In the particle size range of 74 to 214 micrometers, only 25-29% of feed ash is reporting to concentrate. Beyond 214 microns, it is about 35%. At sizes lower than 74 microns about 42% of feed ash is reporting to concentrate. Figure 4.26 shows the ash contents of the Falcon products. The ash content of the concentrate is almost uniformly distributed over the particle size range except at very fine sizes. These results suggest that the Falcon concentrator provides an excellent separation down to 74 microns.

Figure 4.24. Metallurgical performance of the dense medium Falcon in terms of product yield versus product ash (a) Pittsburgh No. 8 fine coal refuse, feed ash $\approx 22\%$. (b) Illinois No. 6 fine coal refuse, feed ash $\approx 14\%$.

Figure 4.25. Classification curves for the performance of the dense medium Falcon treating Pittsburgh No. 8 fine coal refuse, feed ash $\approx$ 22%.

Figure 4.26. Percent ash distribution in the dense medium Falcon products for different particle size fractions. Pittsburgh No. 8 fine coal refuse, feed ash $\approx$ 22%.

The partition curves obtained from the dense medium Falcon process for Pittsburgh No. 8 and Illinois No. 6 samples are shown in Figure 4.27. The dense medium Falcon process provided d_{50} and E_p values of 1.52, 1.63 and 0.06, 0.07 respectively for Pittsburgh No. 8 and Illinois No. 6 coal samples. From these results, the following important observations were made:

- The performance of the dense medium Falcon process is very close to the washability curve, which represents the ideal separation possible by gravity separation techniques. The organic efficiency of the dense medium Falcon process was found to be more than 96%.
- The validation experiments conducted at optimum process variable levels confirm the excellent separation performance achieved in the dense medium Falcon process.
- The Falcon concentrator is an efficient separator for fine coal particles, minimizing the effect of particle size on separation efficiency.

Water-only Falcon Experiments

Based on the previous extensive data generated by the water-only Falcon concentrator (using the pilot-plant scale C10 unit and the full-scale C40 unit) at SIU over the past five years, the following variables were used to evaluate and optimize the water-only Falcon concentrator.

Bowl Speed (20-40 Hz)

Solids concentration (10-30 % by wt.)

Underflow rate (range depends on material)

Feed flow rate (10-30 gallons/minute)

Using a Box-Behnken design (Tables 4.12 and 4.13), a series of 29 experiments were conducted on Illinois No. 6 and Pittsburgh No. 8 fine coal refuse samples.

The experiments with the water-only Falcon Concentrator were conducted using a 10-inch diameter bowl and a slurry pump capable of delivering a feed flow rate of 120 liters per minute. A schematic diagram of the experimental setup is given in Figure 4.28. The feed coal to the Falcon (-48 mesh) was prepared by screening the overflow of the Floatex hindered-bed separator.

Prior to each test, the feed sump was filled with a measured quantity of water and coal sample to achieve the required feed pulp density. The slurry in the feed sump was kept in suspension using stirrers and a re-circulation circuit. After measuring the feed pulp density, the desired feed flow rate was set by adjusting the by-pass valve. The required operating levels of the Falcon concentrator, such as the bowl speed and underflow rate were set. The feed, concentrate and tailing samples were collected after allowing sufficient time for attaining steady-state conditions. The collected samples were screened at 325-mesh to separate the fines fraction and analyzed.

Figure 4.27 Partition curve obtained for the performance of the dense medium Falcon treating (a) Pittsburgh No. 8 fine coal refuse sample (b) Illinois No. 6 fine coal refuse.

Figure 4.28. Schematic diagram of the experimental setup used for the test programs involving the C10 Falcon Concentrator.

Illinois No. 6 fine coal refuse

The data (Table 4.12) were analyzed using the Design Expert software. A quadratic model was fitted to the data and can be written in reduced form for combustible recovery (CR) and ash rejection (AR) as

$$CR = 80.05 + 10.67 * B - 13.84 * C + 18.08 * D - 12.02 * D^2 + 9.21 * B * C + 11.67 * C * D \quad [4.10]$$

and

$$AR = 49.06 - 14.04 * B + 11.29 * C - 11.06 * D + 7.60 * D^2 - 7.08 * C * D \quad [4.11]$$

in which A is the bowl speed (Hz), B the percent solids (by wt), C the underflow rate (lpm), D the feed rate (lpm)

Table 4.12. The design matrix and responses of Box-Behnken test program conducted using the C-10 Falcon Concentrator and water as the medium to treat the 48 x 325 mesh particle size fraction of the Illinois No. 6 coal; feed ash $\approx 13.33\%$; feed total sulfur $\approx 3.12\%$.

Test No.	Bowl Speed (Hz.) A	Feed Solids (% wt.) B	Underflow Rate (lpm) C	Volumetric Feed Rate (lpm) D	Product Ash (%)	Mass Yield (%)	Combustible Recovery (%)
1	30	20	3	37.8	11.5	11.66	22.10
2	30	30	2	113.4	9.31	90.69	94.09
3	30	20	2	75.6	9.31	82.61	86.44
4	30	20	1	37.8	9.23	73.75	77.45
5	30	10	1	75.6	7.89	78.21	83.11
6	30	30	2	37.8	8.50	75.00	66.46
7	20	20	2	113.4	9.10	77.61	81.39
8	30	20	2	75.6	9.04	77.55	81.39
9	40	10	2	75.6	7.65	70.78	75.42
10	30	10	2	113.4	8.08	75.34	79.90
11	20	20	1	75.6	9.42	90.64	94.73
12	20	20	2	37.8	8.61	35.69	37.64
13	30	10	2	37.8	6.77	45.06	48.47
14	20	10	2	75.6	7.69	58.25	62.04
15	40	30	2	75.6	9.85	87.49	91.00
16	30	30	1	75.6	10.69	91.76	94.55
17	30	20	2	75.6	8.89	81.42	85.59
18	30	30	3	75.6	9.14	73.65	77.21
19	20	20	3	75.6	8.92	73.83	77.58
20	30	20	1	113.4	8.98	88.27	92.70
21	30	20	3	113.4	7.85	79.08	84.04
22	20	30	2	75.6	9.85	79.35	82.53
23	30	20	2	75.6	8.84	81.36	85.58
24	40	20	1	75.6	8.42	85.86	90.73
25	40	20	2	113.4	8.82	83.95	88.32
26	40	20	2	37.8	9.31	49.05	51.32
27	40	20	3	75.6	8.02	72.94	77.40
28	30	10	3	75.6	6.50	26.80	28.91
29	30	20	2	75.6	8.87	82.43	86.67

The predicted and actual responses for CR and AR are shown in Figures 4.29 and 4.30. The effects of the operating parameters on each response variable are summarized in the perturbation plots (Figures 4.31 and 4.32). As shown, underflow rate, feed rate and percent solids have the greatest effect on combustible recovery and ash rejection. An increase in the underflow rate decreases the combustible recovery, while increasing the ash rejection. Whereas, an increase in the feed rate increases the combustible recovery and reduces the ash rejection (Figures 4.33 and 4.34). An increase in underflow rate removes higher amount of ash forming minerals, thus improves the ash rejection. However, at a higher underflow rate coarse coal particles are lost to the tailings fraction reducing the combustible recovery. An increase in feed rate reduces the residence time of the coal slurry inside the bowl, thus giving less time for rejection of ash bearing materials to the underflow. Similarly, a high percent solids creates crowding of particles thus minimizing the migration of ash bearing material to underflow, while increasing the combustible recovery. It is interesting to note that the bowl speed do not have much effect on the combustible recovery and ash rejection as per *t*-statistic. It is expected that a higher bowl speed should increase the ash rejection due to increase in the high centrifugal force. However, an increase in bowl speed also reduces the residence time of slurry thus minimizing the effect of high centrifugal force.

The model equations suggest that the effect of percent solids, underflow rate and feed flow rate is highly significant as indicated by *t*-statistic. The model also suggests that combustible recovery is a strong quadratic function of feed flow rate and supported by very low *t*-statistic obtained for the D^2 term.

Figure 4.29. Plot illustrating actual vs. predicted response as obtained from the empirical model for combustible recovery (%); Illinois No. 6 coal; feed ash $\approx$ 13.33%.

Figure 4.30. Plot illustrating actual vs. predicted response as obtained from the empirical model for ash rejection (%); Illinois No. 6 coal, feed ash $\approx$ 13.33%.

Figure 4.31. Perturbation plot showing the effect of the operating parameter values on combustible recovery, Illinois No. 6 refuse material.

Figure 4.32. Perturbation plot showing the effect of the operating parameter values on ash rejection; Illinois No. 6 refuse fine coal.

Figure 4.33. The interactive effect of underflow rate and percent solids values on the combustible recovery response; Illinois No. 6 refuse fine coal.

Figure 4.34. The interactive effect of underflow rate and percent solids values on the ash rejection recovery response, Illinois No. 6 refuse fine coal.

Pittsburgh No. 8 fine coal refuse

The data (Table 4.13) were analyzed using the Design Expert software. A quadratic model was fitted to the data and can be written in reduced form for combustible recovery (CR) and ash rejection (AR) as

$$CR = 78.11 - 0.22*A + 13.18*B - 6.21*C + 9.91*D - 6.31*A^2 - 9.18*B^2 \quad [4.12]$$

and

$$AR = 53.35 - 1.27*A - 13.77*B + 13.47*C - 11.61*D + 7.91*B^2 - 11.67*C^2 \quad [4.13]$$

in which A is the bowl speed (Hz), B the percent solids (by wt.), C the underflow rate (lpm), D the feed rate (lpm).

The predicted and actual responses for CR and AR are shown in Figures 4.35 and 4.36. The effects of the operating parameters on each response variable are summarized in the perturbation plots (Figures 4.37 and 4.38). It is clear from the perturbation plots that underflow rate, feed rate and solids contents have the maximum effect on the combustible recovery and ash rejection. As observed in the treatment of Illinois no. 6 fine coal refuse, the bowl speed does not have much effect on both combustible recovery and ash rejection. Figures 4.39 and 4.41 show that the combustible recovery is greatly affected

by the percent solids and feed rate. A higher percent solid increases the crowding of the particles inside the bowl, minimizing the effective stratification thus affecting the separation process. Hence, more particles report to overflow increasing the combustible recovery and decreasing the ash rejection. A higher underflow rate increases the ash rejection by removing more ash forming minerals with decrease in combustible recovery. A higher feed rate has a similar effect (Figures 4.40 and 4.42).

Table 4.13. The design matrix and responses of Box-Behnken test program conducted using the C-10 Falcon Concentrator and water as the medium to treat the 48 x 325 mesh particle size fraction of the Pittsburgh No. 8 coal; feed ash $\approx 16.50\%$; feed total sulfur $\approx 4.66\%$.

Test No.	Bowl Speed (Hz) A	Feed Solids (% wt.) B	Underflow Rate (lpm) C	Volumetric Feed Rate (lpm) D	Product Ash (%)	Mass Yield (%)	Combustible Recovery (%)
1	30	20	5	37.8	8.87	72.71	78.89
2	30	30	3.5	113.4	14.26	91.55	93.44
3	30	20	3.5	75.6	9.48	71.47	77.01
4	30	20	2	37.8	11.29	80.78	85.31
5	30	10	2	75.6	11.86	59.73	62.67
6	30	30	3.5	37.8	11.84	73.28	76.91
7	20	20	3.5	113.4	13.48	81.36	83.80
8	30	20	3.5	75.6	11.18	73.03	77.22
9	40	10	3.5	75.6	10.82	50.38	53.49
10	30	10	3.5	113.4	8.36	53.75	58.64
11	20	20	2	75.6	14.77	91.00	92.33
12	20	20	3.5	37.8	8.48	47.92	52.21
13	30	10	3.5	37.8	7.43	25.93	28.57
14	20	10	3.5	75.6	7.51	44.40	48.89
15	40	30	3.5	75.6	9.86	70.75	75.92
16	30	30	2	75.6	14.61	91.81	93.33
17	30	20	3.5	75.6	9.87	71.83	77.07
18	30	30	5	75.6	9.27	67.39	72.79
19	20	20	5	75.6	10.13	64.38	68.88
20	30	20	2	113.4	13.17	84.46	87.30
21	30	20	5	113.4	11.41	71.61	75.53
22	20	30	3.5	75.6	9.23	62.58	67.62
23	30	20	3.5	75.6	10.86	70.32	74.63
24	40	20	2	75.6	13.86	88.00	90.25
25	40	20	3.5	113.4	12.16	77.74	81.29
26	40	20	3.5	37.8	12.59	37.66	39.19
27	40	20	5	75.6	11.47	67.32	70.95
28	30	10	5	75.6	8.47	63.87	69.59
29	30	20	3.5	75.6	11.61	76.26	80.24

Figure 4.35. Plot illustrating actual vs. predicted response as obtained from the empirical model for combustibility recovery (%); Pittsburgh No. 8 coal; feed ash $\approx 16.50\%$.

Figure 4.36. Plot illustrating actual vs. predicted response as obtained from the empirical model for ash rejection (%), Pittsburgh No. 8 coal; feed ash $\approx 16.50\%$.

Figure 4.37. Perturbation plot showing the effect of the operating parameter values on combustible recovery, Pittsburgh No. 8 coal.

Figure 4.38. Perturbation plot showing the effect of the operating parameter values on ash rejection, Pittsburgh No. 8 coal.

Figure 4.39. The effect of underflow rate and percent solids values on the combustible recovery response; Pittsburgh No. 8 coal.

Figure 4.40. The effect of underflow rate and feed rate on the ash rejection response; Pittsburgh No. 8 coal.

Figure 4.41. The effect of underflow rate and percent solids values on the ash rejection response; Pittsburgh No. 8 coal.

Figure 4.42. The effect of underflow rate and feed rate values on the ash rejection response; Pittsburgh No. 8 coal.

Process Optimization

The model equations (4.10 to 4.13) were used to optimize the water-only Falcon performance for achieving optimum separation performance. A steepest ascent/descent optimization routine was utilized to maximize/minimize the desirable merit function for simultaneous optimization of multiple responses. The conditions under which minimum product ash could be obtained for a particular target product mass yield are tabulated in Table 4.14 and 4.15 for Illinois No. 6 and Pittsburgh No.8 refuse coals respectively.

Table 4.14. Optimized factor levels to be maintained in order to achieve target separation performance (Illinois No. 6 refuse coal), Feed: -48 mesh.

Run No.	Factor				Predicted Product Ash (%)	Predicted Product Yield (%)
	A	B	C	D		
1	39.18	10.00	1.00	40.44	6.00	68.34
2	31.65	17.85	3.00	113.40	6.99	77.04
3	30.39	26.49	3.00	113.21	8.00	89.70
4	35.65	29.55	2.92	107.11	8.80	92.51
5	33.83	26.87	1.47	113.85	9.74	89.71

Table 4.15. Optimized factor levels to be maintained in order to achieve target separation performance (Pittsburgh No. 8 refuse coal), Feed: -48 mesh.

Run No.	Factor				Predicted Product Ash (%)	Predicted Product Yield (%)
	A	B	C	D		
1	20	30	3.74	37.88	7.98	64.86
2	20	30	3.41	48.50	8.99	69.85
3	20	29.64	3.38	63.29	10.00	73.61
4	40	30	3.09	113.4	11.99	88.47
5	32.91	27	2.34	111.1	13.96	91.84

Experiments were carried out with the Illinois No. 6 and Pittsburgh No. 8 refuse fine coals, under these optimum conditions to validate the model predictions. Figures 4.43 and 4.44 show the partition curves for the optimized samples of Illinois No. 6 and Pittsburgh No. 8 coal fine coal refuse samples. The D_{50} increases with increase in product yield. The D_{50} values for the Illinois No. 6 and Pittsburgh No. 8 fine coal refuse at about 82% and 71% product yields are 1.82 and 1.81 respectively.

Figure 4.43 Partition curve obtained for the optimized samples of the water-only Falcon treating Illinois No. 6 fine coal refuse sample.

Figure 4.44 Partition curve obtained for the optimized samples of the water-only Falcon treating Pittsburgh No. 8 fine coal refuse sample.

The results of the Box-Behnken design and optimized tests are plotted in Figures 4.45 and 4.46. The results for Illinois No. 6 fine coal refuse show that it is possible to obtain a clean coal having 7.76% ash with about 82.07% yield from a feed coal having 13.73% ash with a combustible recovery of 87.78%. The ash rejection is about 55%. The pyritic sulfur content was reduced to 0.15% from 0.51%. The total sulfur content in the Falcon products is in the range between 2.45% to 2.75%. The small reduction in the total sulfur content in the Falcon product is mainly due the presence of higher percentage of other forms of sulfur as compared to pyritic sulfur (0.51%).

The tests results with Pittsburgh No 8 fine coal refuse (Figure 4.46) show that a clean coal containing 8.51% ash with a product yield of 71.73% can be obtained from a feed coal having 16% ash with a combustible recovery and ash rejection of 78% and 61% respectively. The total sulfur content in the feed is reduced to 2.43% from 4.77%, where as the pyritic sulfur was reduced from 2.40% to 0.95%.

Evaluation of Water-Only and Dense-Medium Falcon Processes for Different Feed Characteristic Refuse Pond Samples

The main aim of this task is to treat another refuse sample, which has distinctively different feed characteristics from the one used in the earlier studies, to find out the effect of feed characteristics on the separation performance. The optimum operation conditions identified earlier were used as a starting point for this test program.

The refuse sample from Jader fuels preparation plant, which treats Illinois No. 2 and 3 seams, was collected for this purpose. The sample was homogenized and split into two fractions. One fraction was wet screened to remove + 16 mesh fraction. The -16 mesh was treated in a cyclone to remove - 325 mesh fraction. This fraction (-16 x 325) was used for the heavy media Falcon tests. The feed to the water-only Falcon was prepared by screening the other half of the sample through a 48-mesh screen. The -48 mesh fraction was used for the water-only Falcon studies. The particle size analysis and size-by-size ash and total sulfur contents are given in Table 4.16. The Jader refuse sample contains about 48% ash and 5.43% total sulfur. The experimental conditions for the water-only and heavy medium Falcon tests for the Jader refuse sample were based on the analysis of the results of Pittsburgh No. 8 sample. Since the Jader refuse contains high ash content it is necessary to operate the Falcon at a higher underflow rate and decrease the feed flow rate while carrying water-only Falcon tests.

Analysis of Pittsburgh No. 8 sample results show that the bowl speed, underflow rate and medium density affects the product ash content, where as the product yield is influenced by medium density and underflow rate. The optimized variables on Pittsburgh No. 8 samples reveal that the bowl speed and underflow rate varies between 20 to 30 Hz and 6 to 11 liter/min respectively, with the medium density ranging from 1.35 to 1.5. The Pittsburgh No. 8 sample contains about 5%-10% near gravity material (NGM) having 22% ash. The previous data on Jader refuse samples shows that NGM is about 1 to 4% having an ash content of about 50%. Therefore, the underflow rate of the dense medium Falcon treating Jader refuse has to be increased above 11-liter/ min to facilitate the

rejection of ash forming materials. The experimental conditions and results for water-only and heavy medium Falcon are given in Tables 4.17 and 4.18.

Figure 4.45 Metallurgical performance of the water-only Falcon obtained on the basis of product ash from the treatment of -48-mesh particle size fraction of the Illinois No. 6 fine coal refuse.

Figure 4.46 Metallurgical performance of the water-only Falcon obtained on the basis of product ash from the treatment of -48-mesh particle size fraction of the Pittsburgh No. 8 fine coal refuse.

Table 4.16. Size by size ash, and total sulfur analysis of Jader refuse.

Size fraction (mesh)	Weight (%)	Ash (%)	Total Sulfur (%)
+16	3.18	38.03	4.48
16x28	10.56	51.82	6.89
28x48	16.81	52.35	6.39
48x65	12.23	46.22	5.23
65x100	9.86	36.39	6.13
100x200	13.46	39.89	5.62
200x325	11.86	43.54	6.94
325x400	1.58	42.1	5.19
400x500	2.18	50.94	4.43
-500	18.28	59.56	2.81
TOTAL	100	47.91	5.43

Table 4.17. The experimental conditions and results of test program conducted using the C-10 water-only Falcon Concentrator, Jader refuse coal, feed ash $\approx 41.30\%$, feed total sulfur $\approx 5.32\%$, Feed size 48 x 325 mesh.

Test No.	Bowl Speed (Hz.)	Underflow Rate (lpm)	Volumetric Feed Rate (lpm)	Product Ash (%)	Mass Yield (%)	Combustible Recovery (%)
1	20	5	80	26.35	64.37	80.76
2	20	4	80	27.46	53.57	66.20
3	30	4	80	15.91	50.93	72.96
4	30	5	80	12.61	42.33	63.03
5	30	6	80	16.75	27.85	39.50
6	40	4	80	20.06	55.26	75.26
7	40	5	80	18.91	32.67	45.13
8	30	4	40	13.46	24.06	35.48
9	30	5	40	13.18	16.85	24.93
10	30	6	40	19.13	23.20	31.97
11	40	4	40	20.14	23.05	31.36

Table 4.18 The experimental conditions and results of test program conducted using the C-10 heavy medium Falcon Concentrator treat the -16 mesh particle size fraction of the Jader refuse coal; feed ash $\approx 48.68\%$; feed total sulfur $\approx 6.60\%$.

Test No.	Medium Density (gm/cm ³)	Bowl Speed (Hz.)	Underflow Rate (lpm)	Product Ash (%)	Mass Yield (%)	Combustible Recovery (%)
1	1.4	20	10	35.08	66.84	84.49
2	1.4	20	13	28.92	54.42	75.31
3	1.4	20	16	13.96	17.10	28.65
4	1.4	20	19	19.47	39.98	62.69
5	1.4	25	10	34.64	54.39	69.22
6	1.4	25	13	17.53	35.76	57.42
7	1.4	25	16	27.73	59.27	83.40
8	1.4	25	19	38.08	46.90	56.53
9	1.5	20	10	27.44	53.72	75.89
10	1.5	20	13	34.78	63.26	80.34
11	1.5	20	16	27.28	51.97	73.58
12	1.5	20	19	27.62	43.35	61.09
13	1.5	25	10	26.15	53.11	76.35
14	1.5	25	13	32.23	60.65	80.03
15	1.5	25	16	37.08	58.50	71.66
16	1.5	25	19	28.18	49.91	69.80

Table 4.17 shows that the underflow rate has the significant effect on the product ash and yield. At a very high underflow rate the product ash increases due to the instability of the bed, affecting the separation process. The lower and higher bowl speeds did not significantly reduce the ash content. The tests results along with washability data are presented in Figure 4.47. The results show that it is possible to obtain a clean coal having 12.61% ash with about 42% yield from a feed coal having 41% ash with a combustible recovery of 63%. The pyritic sulfur content is reduced from 6.60% to 2.07%.

The distribution curves and generalized distribution curve are shown in Figures 4.48 and 4.49. The D_{50} increases with increase in yield. It is interesting to note that the D_{50} values vary between 1.41 to 1.64. The observed low D_{50} value may be due to the presence of high amount of pyritic sulfur, which may be acting like a heavy medium. Also, a very high underflow rate usually decreases the cut density. The generalized partition curve (Figure 4.49) shows that it is possible to get a partition curve independent of operating and process variables.

Figure 4.47. Metallurgical performance of the water-only Falcon obtained on the basis of product ash from the treatment of -48-mesh particle size fraction of the Jader refuse. Feed ash - 41.30%.

Figure 4.48. Partition curves obtained for the performance of the water-only Falcon process treating Jader refuse. Feed ash - 41.30%.

Figure 4.49. Generalized partition curve obtained for the performance of the water-only Falcon process treating Jader refuse. Feed ash - 41.30%.

As expected the medium density, bowl speed and underflow rate have the greatest influence on product ash and yield of the dense medium Falcon. An increase in medium density increases the separation density, where as an increase in bowl speed from 20 Hz to 25 Hz improves the separation process. A very high underflow rate is detrimental to the process, as it reduces the stability of the particle bed. The tests results along with washability data are presented in Figure 4.50. It is possible to obtain a clean coal having 17.53% ash with about 36% yield from a feed coal having 49% ash with a combustible recovery of 57%. The total sulfur content is reduced from 6.60% to 2.69%, with a sulfur rejection of 85%. The pyritic sulfur was reduced to 1.55% from 4.43%. Figure 4.50 shows that the Falcon data is very close to washability data, indicating the superior performance of the separator. The partition curves and generalized partition curve for different product yields are shown in Figures 4.51 and 4.52. At about 17.53% product ash and 36% product yield the D_{50} is 1.5 with an E_p value of 0.1. Figure 4.52 shows that the applicability of the generalized partition curve for heavy media Falcon, which was originally observed for heavy medium cyclone. The curve independent of operating and process variable can be used for scale-up procedures.

From these results the following observations can be made,

- The separation performance of the water-only and dense medium Falcon is close to the washability curve
- The results show that the Falcon concentrator is able to process feed coals having different characteristics by controlling the operating and process variables. Thus

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Figure 4.50. Metallurgical performance of the heavy medium Falcon obtained on the basis of product ash from the treatment of -16 x 325 mesh particle size fraction of the Jader refuse. Feed ash - 48.68%.

Figure 4.51. Partition curves obtained for the performance of the heavy medium Falcon

Figure 4.52. Generalized partition curve obtained for the performance of the heavy medium Falcon process treating Jader refuse. Feed ash - 48.68%.

Evaluation of Water-Only Falcon Process for Separation of Clay-Rich Fraction from Acid Generating Materials

The objective of this task is to treat the tailings of the water-only Falcon or dense-medium circuit including flotation, to produce a clay-rich fraction for land reclamation and another fraction with acid generating materials.

The mixed-tailing samples were prepared by mixing the tailings of the Floatex, Falcon and Jameson cell of Pittsburgh No. 8 and Illinois No. 6 fine coal refuse materials. The individual tailing samples from each process were obtained while preparing samples for participating organizations.

The following variables of the Falcon concentrator were used to evaluate the separation performance using a 2^3 factorial experimental design for this study.

Bowl Speed

Underflow rate
Feed flow rate
Pittsburgh No. 8 fine coal refuse mixed tailings

The data (Table 4.19) were analyzed using Design Expert software. The following model (Eq. 4.14) was fitted to the data to quantify the effect of each parameter and their interactions. The predicted and actual values are shown in Figure 4.53.

$$\text{Total sulfur rejection} = 43.01 + 3.40*A + 9.83*B - 7.12*C + 1.79*A*B + 3.19*A*C - 3.53*B*C \quad [4.14]$$

in which A is the bowl speed (Hz), B the underflow rate (lpm), C the volumetric feed rate (lpm)

The coefficients of different parameters of equation 4.14, clearly show that the underflow rate has a significant effect on total sulfur rejection followed by feed flow rate as indicated by t -statistic. The bowl speed has small effect on total sulfur rejection as indicated by the magnitude of the coefficient ' A ' and t -statistic. However, an increase in bowl speed has positive effect on total sulfur rejection. These results indicate that lower feed rate provides better total sulfur rejection.

Table 4.19. A 2^3 design matrix and responses for experiments conducted on the water-only Falcon using tailings generated from the treatment of Pittsburgh No. 8 fine coal refuse; feed total sulfur $\approx 7.63\%$.

Test No.	Bowl Speed (Hz) A	Underflow Rate (lpm) B	Volumetric Feed Rate (lpm) C	Total Sulfur Rejection to Underflow (%)	Overflow Mass Yield (%)	Overflow Product Total Sulfur (%)
1	20	3	60	61.58	65.82	3.87
2	20	1	60	38.26	83.37	4.91
3	20	3	120	33.71	78.62	5.59
4	40	1	60	35.27	89.41	4.80
5	30	2	90	47.14	80.57	4.35
6	20	1	120	24.86	88.33	5.64
7	40	3	120	50.65	75.92	4.31
8	40	1	120	34.31	85.23	5.11
9	40	3	60	65.41	59.57	3.85

Figure 4.53. A comparison of the actual versus predicted total sulfur rejection values (%) as obtained from the empirical model (Eq. [4.14]).

The test results revealed that it is possible to obtain a clay rich fraction (Falcon overflow) having 4.35% total sulfur with about 80% mass yield (Figure 4.54). The Falcon underflow, which is a pyrite rich fraction, contains about 16.30% total sulfur. These results indicate that it is possible to produce a clay rich fraction having total sulfur content (4.35%) less than the total sulfur contained in the original Pittsburgh No. 8 coal fines (4.75%). The total sulfur rejection was about 47%. Based on the discussions with Dr. Y.P. Chugh, it was understood that it was necessary to have some clay content in the Falcon tailings, to facilitate acid neutralization. Hence, using the Design Expert software, the near optimum parameters of the Falcon were evaluated to optimize the total sulfur rejection, keeping the total sulfur content of the Falcon tailings to about 14%. Some of the solutions by Design Expert software are given in Table 4.20.

These results clearly indicate that it is necessary to maximize the underflow rate, keeping the bowl speed and feed flow rate at higher and lower level respectively. A series of experiments were carried out at and near the vicinity (Table 4.20) of the parameters suggested by the Design expert software. The results are given in Table 4.21.

These results indicate that a sulfur rich fraction and clay rich fraction having total sulfur contents of 13.35% and 3.54% respectively can be produced from mixed tailings having a total sulfur content of 7.72%. The pyritic sulfur content in the mixed tailings was reduced to 2.76% from 5.73%. The Pittsburgh No. 8 refuse coal contains about 3.21% pyritic sulfur.

Figure 4.54. Metallurgical performance of the water-only Falcon treating the Pittsburgh No. 8 fine coal refuse mixed tailings; feed total sulfur $\approx 7.63\%$.

Table 4.20. Predicted factor levels and their corresponding metallurgical performances (Pittsburgh No. 8 fine coal refuse mixed-tailings).

Run No	Bowl Speed (Hz.)	Underflow Rate (lpm)	Volumetric Feed Rate (lpm)	Falcon Product Total Sulfur (Clay rich) (%)	Falcon Tails Total Sulfur (Pyrite rich) %	Total Sulfur Rejection %
	A	B	C			
1	40	3	60	3.74	13.75	65.49
2	39.33	3	60	3.75	13.74	65.36
3	40	3	61.58	3.76	13.81	65.00
4	40	3	62.31	3.77	13.84	64.91

Table 4.21. Actual factor levels maintained and their corresponding metallurgical performances (Pittsburgh No. 8 fine coal refuse mixed-tailings), total sulfur = 7.72%.

Run No.	Bowl Speed (Hz.)	Underflow Rate (lpm)	Volumetric Feed Rate (lpm)	Falcon Product Total Sulfur (Clay rich) (%)	Falcon Tails Total Sulfur (Pyrite rich) (%)	Total Sulfur Rejection (%)
	A	B	C			
1	40	3	60	3.85	14.30	62.39
2	40	3	80	4.57	12.91	56.79
3	35	3.5	60	3.21	12.26	71.09
4	40	3	60	3.54	13.35	65.21

Illinois No. 6 fine coal refuse mixed tailings

The data (Table 4.22) were analyzed using Design Expert software. The following model (Eq. 4.15) was fitted to the data to quantify the effect of each parameter and their interactions. The predicted and actual values are shown in Figure 4.55.

$$\text{Total sulfur rejection} = 45.45 - 1.41 \cdot A + 6.01 \cdot B - 1.62 \cdot C - 6.72 \cdot B \cdot C \quad [4.15]$$

in which A is the bowl speed (Hz), B the underflow rate (lpm), C the volumetric feed rate (lpm).

The coefficients of different parameters of equation 4.15, clearly show that the underflow rate has a significant effect on total sulfur rejection followed by feed flow rate as indicated by t -statistic. The bowl speed has small effect on total sulfur rejection as indicated by the magnitude of the coefficient ' A ' and t -statistic. These results indicate that lower feed rate and higher underflow rate provides better total sulfur rejection.

The results of the 2^3 design experiments (Table 4.22) show that the total sulfur content in the overflow generally increases with increase in mass yield to overflow. However, the total sulfur content in the overflow varies between narrow ranges of 1.53% to 1.85%, because of lower percent of pyritic sulfur in the refuse sample. The total sulfur content in the Falcon tailings varies between 2.59% to 3.56%. Hence, the tailings obtained from the processing of Illinois No. 6 fine coal refuse is not suitable for producing a pyritic rich fraction because of presence of other forms of sulfur than pyritic sulfur.

Table 4.22. A 2^3 design matrix and responses for experiments conducted on the water-only Falcon using Illinois No. 6 fine coal refuse mixed tailings; feed total sulfur $\approx 2.50\%$.

Test No.	Bowl Speed (Hz.) A	Underflow Rate (lpm) B	Volumetric Feed Rate (lpm) C	Total Sulfur Rejection to Underflow (%)	Overflow Mass Yield (%)	Overflow Product Total Sulfur (%)
1	40	1	120	42.53	78.95	1.82
2	20	6	60	61.35	63.16	1.53
3	20	1	120	46.54	77.26	1.73
4	40	1	60	31.05	93.18	1.85
5	40	6	120	44.35	87.50	1.59
6	20	1	60	37.64	91.17	1.71
7	40	6	60	58.26	66.47	1.57
8	20	6	120	41.91	82.51	1.76

Figure 4.55. A comparison of the actual versus predicted total sulfur rejection values (%) as obtained from the empirical model (Eq. [4.15]) for Illinois No. 6 fine coal refuse mixed tails; feed total sulfur $\approx 2.50\%$.

Process Automation and Control

The feed characteristics and composition of the refuse pond vary widely from pond to pond and even within a pond, from location to location. Hence, the advanced fine coal cleaning technologies developed for treating the refuse pond sample should have an efficient process control system, which can quickly modify the operating conditions to achieve optimum separation performance despite the wide variation in feed characteristics. The aim of this task is, therefore, to develop a control strategy for the Falcon Concentrator, using on-line coal slurry analyzer to adjust its design parameters suitably to varying feed characteristics.

The recent development in the design of underflow nozzles makes the Falcon Concentrator process amenable to on-line control. The critical operating parameters of Falcon process can be centrally controlled to achieve the desired product quality. Thus, an AMDEL on-line coal slurry analyzer, which was developed in Australia, was evaluated at SIUC for the purposes of adjusting operating parameter values, especially underflow mass flow rate, when the assay and/or mass flow rate in the feed stream varies. Results from the dense medium Falcon tests indicate that the bowl speed is the most effective parameter for improving product grades. Thus, on-stream analysis of the product and/or tailing streams by the AMDEL could provide efficient control of the product grade through manipulation of the bowl speed. The results obtained from statistically designed experiments were used to develop an on-line control strategy to

achieve optimum performance from the Falcon Concentrator. The system is being initially developed for the C10 Falcon unit and will be demonstrated in the field during Phase II of this project.

Experiments Performed

Over the past five years, SIUC has generated a vast database on the performance of the water-only Falcon process treating different feed characteristic coals. These test programs were conducted both on pilot-plant-scale C10 unit (2 tones/hr) and full-scale C40 unit (100 tones/hr). Based on this knowledge and the current results, four critical operating variables were selected for detailed parametric study. It should be noted that the washability characteristics of the refuse pond material would be much different from the typical run-of-mine coal and, hence, re-evaluation of the effect of different operating and design variables was essential to achieve optimum performance. In this respect, four key operating parameters were examined in detail for process optimization studies. They are feed ash, feed solids content, underflow rate and bowl speed. Experiments were performed to establish the effect of aforementioned parameters on the ash value and the yield. The Pittsburgh No. 8 fine coal refuse was used to conduct the experiments with Falcon. The sample was screened to prepare -48-mesh coal sample for the Falcon.

Experimental Conditions

Experiments using the C10 Falcon system described previously were performed in order to collect enough data to generate a model that will be used to direct the control system. The development of the model involved a randomized Box-Behnken statistical design methodology. Four variables were evaluated, namely, the feed ash content, feed percent solids, underflow rate and bowl speed. The ranges of the variables tested are presented in Table 4.23. The feed ash content was varied for a given material by extracting a predetermined amount of tailings material from the closed-loop Falcon system or by the addition of ash-bearing material derived from the same sample. The detailed list of experiments performed is presented in Table 4.24.

Table 4.23 Ranges of variables evaluated for development of a model to control the Falcon concentrator.

Parameters	Experimental range
Feed ash, %	25-35
Percent Solids, %	17-27
Bowl Speed, Hz	20-40
Underflow rate (lpm)	1-5

Approach to the Modeling

The AMDEL Coal Slurry Analyzer (CSA) unit, provides the ash content and percent solids of the appropriate slurry stream, which is the clean coal and feed streams in the case of methods 1 and 2, respectively. It is incorporated with a signal analyzer, so that the parameters of the Falcon concentrator can be controlled. Two methods were envisioned for the automatic control of Falcon concentrator using AMDEL unit. The method 2, which is the indirect control system, was chosen for evaluation in this study. It has to be noted however that a better control strategy would utilize the simultaneous analysis of both the product and reject streams.

Method 1: Direct Control of the Clean-Coal Product

In this method, the sensors of the AMDEL analyzer are located in the clean-coal slurry stream. Any deviation from the preset ash value of the clean coal will trigger the mechanism to adjust the bowl speed stepwise until the ash content is within the acceptable range. Once bowl speed has been adjusted, underflow rate of Falcon concentrator will be varied so as to obtain the maximum yield through the overflow. This technique of control is simple providing effective control over the ash content of the clean coal. However, since the AMDEL unit already available is unable to measure volumetric or mass flow rate, this technique requires additional sensors for control.

Method 2: Indirect Control of the Clean-Coal Product

Indirect control of the clean-coal product involves on-line measurement of the feed slurry. Since only the feed slurry is to be monitored, ash content and mass yield of clean coal and those values related to tailings are computed using the developed models. The computation is based on the developed empirical equation relating the feed ash, solids content, underflow rate and bowl speed, to the ash content and yield of the clean coal-product. In this respect, for different feed ash content and solid contents, the effect of bowl speed and underflow rate on the quality of the products can be monitored.

Analysis of data

The data from the Box-Behnken design (Table 4.24) was used to develop empirical relationships describing the effect of the response variables such as, product ash and yield as a function of the operating variables. These empirical relations provide the degree of effect of individual variables and their interactions. The empirical relations in the coded form can be written as,

$$\begin{aligned} \text{Product ash (\%)} = & 8.82 + 4.26*A + 1.84*B - 2.185*C - 1.08*D + 1.14*A^2 \\ & + 2.01*D^2 - 2.21*A*C \end{aligned} \quad [4.16]$$

$$\begin{aligned} \text{Product Yield (\%)} = & 66.76 + 14.89*A + 12.32*B - 13.49*C + 0.2*D \\ & - 10.91A^2 - 8.18*A*D \end{aligned} \quad [4.17]$$

in which A is the feed ash (%), B the percent solids (by wt.), C the under flow rate (lpm), D the bowl speed.

These empirical relationships allow the determination of the optimum parameter values providing maximum yield over a range of ash and yield contents.

Table 4.24. List of experiments performed in accordance with the Box-Behnken statistical experimental design methodology for development of optimization equations for online control of the Falcon concentrator. Pittsburgh No. 8 fine coal refuse, Feed ash = 22.85%, Feed size -48 mesh.

Run No.	Feed Ash (%) (Hz.) A	Percent Solids (%) B	Underflow Rate (lpm) C	Bowl Speed (Hz.) D	Product Ash (%)	Product Yield (%)
1	17.46	15	3.5	30	5.34	32.59
2	25.75	15	3.5	30	13.53	70.22
3	17.46	25	3.5	30	7.67	67.34
4	25.75	25	3.5	30	15.57	73.78
5	21.61	20	1	20	14.16	85.66
6	21.61	20	6	20	12.56	60.97
7	21.61	20	1	40	12.78	84.80
8	21.61	20	6	40	7.75	62.24
9	17.46	20	3.5	20	7.45	22.76
10	25.75	20	3.5	20	16.49	72.36
11	17.46	20	3.5	40	6.43	57.87
12	25.75	20	3.5	40	16.14	74.72
13	21.61	15	1	30	10.12	76.15
14	21.61	25	1	30	13.51	85.13
15	21.61	15	6	30	5.96	45.46
16	21.61	25	6	30	8.7	66.48
17	17.46	20	1	30	6.12	46.41
18	25.75	20	1	30	18.71	85.56
19	17.46	20	6	30	5.23	18.79
20	25.75	20	6	30	8.98	47.84
21	21.61	15	3.5	20	9.31	56.66
22	21.61	25	3.5	20	13.76	80.33
23	21.61	15	3.5	40	5.26	22.89
24	21.61	25	3.5	40	12.4	78.85
25	21.61	20	3.5	30	8.24	67.43
26	21.61	20	3.5	30	7.44	66.14
27	21.61	20	3.5	30	8.08	65.58
28	21.61	20	3.5	30	7.72	64.76
29	21.61	20	3.5	30	8.24	65.44

The coefficients of Eqs. [4.16] to [4.17] and their significance are provided in Tables 4.25 and 4.26. The associated p-values ("Prob > |t|") are interpreted as the probability of realizing a coefficient as large as that observed, when the true coefficient equals zero. In other words, small values of p (less than 0.05) indicate significant coefficients in the model. The variance inflation factor (VIF) measures how much the variance of the model is inflated by the lack of orthogonality in the design. If the factor is orthogonal to all the other factors in the model, the VIF is 1.0. Table 4.25 shows that, for product ash content, all the parameters are important. The interaction between feed ash and bowl speed is also quite significant. Only three parameters were found to significantly affect the product mass yield, i.e., feed ash, percent solids and underflow rate (Table 4.26). The significance of each parameter on product ash, and yield are pictorially depicted using perturbation plots (Figure 4.56 (a) and (b)). It can be concluded that feed ash, percent solids and underflow rate significantly affect both responses.

Figures 4.57 and 4.58 show that the feed ash and percent solids have considerable effect on both product ash and yield. However, the feed ash has significant effect on the product ash compared to the percent solids. Therefore, an abrupt change in the feed ash adversely affects the product grade. The feed ash and percent solids have similar effect on the product yield, i.e. they both increase the product yield. This shows the importance of automation, to control the product ash and yield with varying feed characteristics.

Table 4.25. Least square coefficients of the model equation for product ash with a test of their significance. ($R^2 = 0.92$).

Factor	Coefficient	Prob > t	VIF
Intercept	8.82159		
A - Feed ash	4.265	< 0.0001	1
B - PercentSolids	1.84083	< 0.0001	1
C - U/F rate	-2.185	< 0.0001	1
D - Bowl speed	-1.08083	0.0067	1
A ²	1.14912	0.0244	1
D ²	2.00287	0.0004	1
AC	-2.21	0.0019	1

Table 4.26. Least square coefficients of the model equation for product yield with a test of their significance. ($R^2 = 0.86$).

Factor	Coefficient	Prob > t	VIF
Intercept	66.7637		
A-Feed ash	14.8927	< 0.0001	1
B-Percent solids	12.3279	0.0005	1
C-Underflow rate	-13.4943	0.0002	1
D-Bowl speed	0.21832	0.9427	1
A ²	-10.9098	0.0109	1
AD	-8.1869	0.1297	1

(a)

(b)

Figure 4.56. Perturbation plots showing the parameter effects on (a) product ash, and (b) product mass yield; Pittsburgh No. 8 6 refuse material.

Figure 4.57. The effect of percent solids and feed ash on the product ash response; Pittsburgh No. 8 refuse material.

Figure 4.58. The effect of percent solids and feed ash on the product yield response; Pittsburgh No. 8 refuse material.

Control Algorithm

The algorithm for control of the Falcon concentrator is as follows:

1. Collect the feed and solids ratio data from AMDEL.
2. Compute the required bowl speed and underflow rate to maintain a given product grade and yield, given the developed empirical models.
3. Set the bowl speed and underflow rate.
4. Go to step 1.

Work to be performed

After programming the empirical model and the control algorithm loop in a PC using Labview software, experiments will be conducted to verify the amenability of the Falcon Concentrator for process control. The schematic diagram of the automation and control of the water-only Falcon is given in Figure 4.59.

Figure 4.59. Schematic diagram of the automation of the water-only Falcon concentrator.

- The dense medium Falcon was able to achieve a separation density (d_{50}) of 1.52 at an Ep value of 0.06 while treating Pittsburgh No. 8 sample.
- A clean coal product containing 8.52% ash with 73.43% product yield was achieved from the dense medium Falcon process treating the Pittsburgh No. 8 refuse coal sample having a feed ash content of 22%. The pyritic sulfur content was reduced to 1.23% from 3.41%.
- The results with Illinois No. 6 refuse coal showed that it is possible to obtain a clean coal having 7.25% ash and 0.28% pyritic sulfur with a clean coal yield of 89.85% from a feed coal having 14.23% ash and 0.53% pyritic sulfur.
- To evaluate the variability of the feed characteristics on the Falcon performance, refuse sample from Jader fuels preparation plant was collected and prepared for the water-only and dense medium Falcon tests. The results of water-only Falcon show that it is possible to obtain a clean coal having 12.61% ash with about 42% yield from a feed coal having 41% ash with a combustible recovery of 63%. The pyritic sulfur content is reduced from 6.60% to 2.07%.
- The results with dense medium Falcon using Jader refuse show that it is possible to obtain a clean coal having 17.53% ash with about 36% yield from a feed coal having 49% ash with a combustible recovery of 57%. The total sulfur content is reduced from 6.60% to 2.69%, with a sulfur rejection of 85%. The pyritic sulfur was reduced to 1.55% from 4.43%.
- Optimization of the Falcon process parameters to produce a sulfur rich and clay rich fractions from tailings obtained from processing of Pittsburgh No. 8 refuse coal was carried out. It is possible to obtain a sulfur and clay rich fractions containing total sulfur contents of 13.35% and 3.54% respectively, from a feed having total sulfur content of 7.72%. The pyritic sulfur content in the mixed tailings was reduced to 2.76% from 5.73%. The Pittsburgh No. 8 refuse coal contains about 3.21% pyritic sulfur.
- The processing of tailings obtained from the treatment of Illinois No. 6 refuse coal to produce clay and sulfur rich fractions showed that the total sulfur content in the overflow (clay rich) varies between a narrow range of 1.53% to 1.85%, due to the presence of lower percent of pyritic sulfur content. The total sulfur content in the Falcon tailings varies between 2.59% to 3.56%.
- The experiments results with the variation of feed ash and percent solids show that both the product ash and yield are greatly affected.

ACKNOWLEDGEMENTS

In addition to the funding support by the U. S. Department of Energy, the investigators extend their gratitude to Dr. Ken Ho, Program Manager, Illinois Clean Coal Institute for his keen interest and continued support for Enhanced Gravity Concentration research at SIUC. The

investigators greatly appreciate the cost sharing and technical consultation support provided by Falcon Concentrators Inc. The efforts of Mr. Han Ping, Graduate Student at SIUC, in assisting the conduction of experiments and sample analysis are also appreciated. Appreciation is also due to Mr. Scott Mofield and Mr. Bob Fox for providing technical support during the entire course of experimentation.

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Chapter 5

Magnetic Separation

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July 2000

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SUMMARY OF WORK

Development and Demonstration of Integrated Carbon Recovery Systems from Fine Coal Processing Waste

(Summary of work completed as part of Phase I Project)

Task 4.2 – Evaluation of Media Recovery Circuit

Tasks Proposed

1. Laboratory tests will be conducted using an electromagnet wet drum at Eriez Magnetics. A range of operating conditions and circuit configurations will be studied. Specifically, tests will be conducted to evaluate the following parameters: a. feed rate, b. feed solids loading, c. feed magnetics loading, and d. magnetic field strength.

Status: Test program was completed as described on the product and tailing samples collected from the Falcon concentrator.

2. Based on the parameter evaluation test results, several circuits will be examined including rougher/cleaner and rougher/scavenger configurations.

Status: The test results indicated that a single rougher stage can achieve nearly 100% recovery of the magnetite. Therefore, no other circuits were evaluated.

3. Product quality and recovery will be evaluated using a Davis Tube separator.

Status: All samples including the original magnetite material were analyzed using the Davis Tube and all analyses are currently complete.

Additional Tasks Accomplished

1. All samples collected from the wet drum separator and the Davis Tube were analyzed for ash content.
2. The behavior of the fine coal and associated gangue particles in the wet drum magnetic separator was analyzed to quantify the parameter effects on final clean coal quality.

ABSTRACT

Treatment of the product streams generated from the dense medium Falcon process was investigated for the recovery of the ultrafine magnetite and the production of a final clean coal product. The process streams were initially screened at 65 mesh to remove the coarse material and screen underflow subsequently treated in a laboratory Eriez L-8 wet drum separator. The drum separator was successful in recovering nearly 100% of the magnetite over a wide range of operating conditions in a single rougher process stage. However, high feed solid concentrations resulted in a significant recovery of non-magnetic material to the magnetite-rich process stream from the drum separator, which was minimized at about 6% at the lowest solid concentration. Low volumetric feed flow rates were needed to achieve ash contents below 10% in the +325 fraction of the non-magnetic process stream. Magnetic field strength and feed solids content also had minor affects on the final product grade.

INTRODUCTION AND PROBLEM STATEMENT

The application of dense medium in the Falcon Concentrator requires the recovery of the ultrafine magnetite from both the product and refuse process streams. Efficient magnetite recovery has been cited as a significant factor in the application of dense medium cyclones used to treat 28 x 100 mesh fine coal. The production of a product from a traditional dense medium process generally utilizes a drain-and-rinse screen to separate the clean coal from the magnetite. The screen overflow material is the clean coal while the underflow stream from the rinse portion is subjected to magnetic drum separators to recover the magnetite from the highly diluted suspension. The majority of the magnetite loss is associated with the ultrafine particle size fractions and the screening process.

In the dense medium application of the Falcon Concentrator, the coal is cleaned to a particle size as low as 325 mesh (44 μm). Screening of the material at 325 mesh to remove the magnetite from the clean coal is not economically feasible due to the difficulty in recovering the magnetite through the screen. Therefore, product generation is required from the magnetic drum separators.

In addition, efficient cleaning of coal using a dense medium process requires that the medium maintains stability of the particle suspension throughout the process. In the Falcon Concentrator, higher centrifugal forces than those traditional applied require the use of a higher grade of magnetite, or, in more precise terms, a finer magnetite. As such, the ability of the drum separators to recover the magnetite is compromised. However, new drum separators are available that improves the recovery rate of ultrafine magnetic particles.

GOALS AND SPECIFIC OBJECTIVES

The aim of this task will be to develop an efficient magnetic recovery circuit using Eriez Magnetic Separators. Recent advances in separator design by Eriez Magnetics ensure that present day units achieve high upgrade ratios with superior magnetite recovery. In fact, the Eriez design has evolved to the point where current machine capabilities are quoted to guarantee over 99% magnetite recovery. One of the important features of these separators is that the magnetic intensity can be varied over a wide range. The magnetite to be used in this investigation is 99% -325 mesh and, thus, should be recoverable using conventional wet drums.

In the test circuit, all of the product and reject solids report to the magnetic separators although it is possible that a pre-screening step could be used to remove the coarse (e.g., +100 mesh) material. Without pre-screening, the magnetics loading will be quite high. Additionally, the non-magnetic solids loading will also be extremely high possibly resulting in media contamination problems.

To evaluate the effect of media and contaminant loading on magnetic separation, a series of laboratory tests was conducted using an electromagnet wet drum provided by Eriez Magnetics. A range of operating conditions and circuit configurations was studied. Specifically, tests were conducted to evaluate the following parameters:

- Feed rate,
- Feed solids loading,
- Feed magnetics loading,
- Magnetic field strength.

In addition, the final clean coal product is produced from the drain portion of a coarse screen and the non-magnetic underflow stream of the wet drum separator. Thus, the ability of the process to produce the final clean coal produced were evaluated. Product quality and recovery were analyzed using a Davis Tube separator.

PERTINENT LITERATURE REVIEW

The application of dense medium cyclones to clean 1.0 x 0.15 mm coal has been successfully achieved at three U. S. coal preparation plants and several other cleaning plants in South Africa and China (Osborne, 1988). In a detailed study, Stoessner et al., (1988) found that highly efficient fine coal cleaning is achievable with commercial grade magnetite if efficient sliming of the feed and effective control of medium characteristics is realized. However, the economical viability of the dense medium cyclone application is highly dependent on the amount of magnetite recovered.

In the commercial circuits, the magnetite recovery system employs rapped/vibrating sieve-bends or high frequency Derrick screens to drain and rinse the magnetite from the clean coal and tailings material. Subsequently, the underflow stream from the rinse

screen is treated in magnetic drum separators arranged in a rougher-scavenger circuit. Using this strategy, magnetite consumption from the industrial units have been reported to be in the range of 1.0 – 1.4 kg/ton (2.2 – 3.0 lbs/ton) of clean coal (Osborne, 1988).

Recently, Custom Coals Corporation through funding from the U. S. Department of Energy installed and tested a fine coal circuit that utilized micronized-magnetite to clean 300 x 25 μm (48 x 500 mesh) raw coal in a heavy media cyclone (Torak and Suardini, 1997). Magnetite having a substantially lower mean particle size of around 5 μm was tested in the investigation as compared to the near 20 μm mean size of the conventional magnetite. When using 100 mesh screen decks, the magnetite loss for a 10 μm mean particle size material was 1.9 – 2.1 kg/ton (4.1 to 4.6 lb/ton) for the entire circuit, which included Climax wet drum magnetic separators in a rougher-scavenger arrangement. Direct feeding of the slurry to the wet drum circuit resulted in the lowest magnetite loss of about 1.7 kg/ton (3.8 lb/ton). However, the relatively high magnetite losses were partially explained by the low magnetic strength of the magnetite used. In addition, the stability and quality of the recirculating magnetite suspension was found to deteriorate with a decrease in magnetite particle size.

EXPERIMENTAL STUDIES AND DATA ANALYSIS

Apparatus & Experimental Procedure

Magnetite recovery was investigated by continuously operating a wet drum unit in an open circuit arrangement. The coal-magnetite feed slurry was placed into a 30 gallon sump. A pump was used to recirculate the slurry to provide sufficient agitation to maintain a suspension. Representative samples of the feed were taken periodically from the recirculation line. A peristaltic pump fed the drum separator from a point near the pump discharge.

The magnetic separator used to evaluate magnetite recovery in this investigation was a Eriez L-8 laboratory wet drum unit that is operable in continuous mode at a feed flow rate up to 8 gallons/minute. The drum was 12 inches in diameter and 7.5 inches wide with a rotational speed of 50 rpm. An electromagnetic element was used which allows adjustment of the magnetic field intensity by controlling the applied D-C voltage. As such, magnetic intensity values of 1000 and 1100 gauss, which corresponds to those applied by full-scale 30-inch and 36-inch diameter units, were used thereby allowing easy scale-up of the process data.

Figure 5.1. Schematic of the Eriez L-8 laboratory wet drum separator.

Based on previous experience by Eriez Magnetics personnel, it was decided that successful commercial magnetite recovery required pre-screening of the process streams to remove the coarse material. A significant amount of coarse coal particles reporting to the magnetic separator are typically recovered in the magnetic concentrate and subsequently leads to destabilization of the magnetite suspension. Therefore, the process streams in this investigation were pre-screened at 65 mesh and the magnetite recovery assessment program performed on the -65 mesh fraction. In practice, screening the product streams at 65 mesh rather than 100 or 200 mesh results in significantly greater magnetite recovery values.

The test program involved an evaluation of the volumetric feed rate and solids content effects at two field strengths (i.e., 1000 and 1100 gauss). The number of tests conducted was 18. The experimental design performed for each field strength is provided in Table 5.1.

The products (magnetic concentrate and non-magnetic stream) generated from each of the tests were analyzed for magnetics content using the Davis Tube. The field strength applied in the Davis tube analyses was predetermined by examination of the original feed magnetite material. All magnetic and non-magnetic samples obtained from the Davis Tube were analyzed for ash content to determine the behavior of the coal and the associated ash-forming material in the drum separator.

Table 5.1. Experimental program conducted using a magnetic field strength of 1000 gauss and repeated every even test utilizing a strength of 1100 gauss.

Test Number	Feed Volumetric Flow Rate (gallons/min)	Feed Solids Concentration (% by weight)
1	2	30
3	5	30
5	8	30
7	2	20
9	5	20
11	8	20
13	2	10
15	5	10
17	8	10

Samples

A fifty-five gallon drum sample of the coal-magnetite material from the product stream of the Falcon concentrator was provided by Southern Illinois University. In addition, a five gallon bucket sample of the tailings stream was also evaluated for magnetite recovery. Since the solids contents of both samples exceeded 65% by weight, water was added to the slurry to reduce the solids content to a more typical concentration of 10% to 30% by weight.

A sample of the original magnetite material was also provided for quality analysis. The magnetite used in the investigation was originally obtained through Southern Illinois University from Pea Ridge Iron Ore Company located in Missouri, U. S. A.. The particle size distribution of the magnetite, which was obtained using a Microtrac, indicated that 99% of the material had a particle size less than 44 μm . The complete particle size distribution is provided in Figure 5.2.

To determine the distribution of magnetic strengths among the particles in the magnetite sample, a series of Davie tubes analyses at different field strengths. Each analysis required about 2.5 grams of material that was treated for 2 minutes each. Afterward, the free material and the magnetically entrapped material were collected separately, filtered dried and weighed and analyzed for ash content. An additional series of tests using a 3 minute test period was performed under the same conditions. As shown in Figure 5.3, 100% of the magnetite reported to the magnet at a field strength of 2400 gauss. This finding was nearly equal for both the 2 and 3 minute durations. Therefore, a field strength of 2500 gauss for two minutes was used in all Davies Tube analyses conducted on the wet drum separator samples.

Figure 5.2 Particle size distribution of the magnetite sample from Pea Ridge iron ore company.

Figure 5.3 Magnetics distribution as a function of field strength for the Pea Ridge magnetite sample.

RESULTS AND DISCUSSION

Magnetite Recovery

The Falcon product sample generated from the treatment of the Pittsburgh No.8 refuse sample contained approximately 88% magnetics and the ash content of the non-magnetic fraction was 27.62%. The +325 mesh portion of the non-magnetic material in the product stream represents the final product from the Falcon dense medium process. The ash content of this material in the product provided by Southern Illinois University was 10.25%, which represented nearly 53% of the total non-magnetic material. The relatively high ash content of 27.62% indicates the need for an efficient desliming process to realize the final clean coal product.

The results achieved from the test program using the Eriez wet drum separator are shown in Table 5.2. Using only a rougher recovery stage, near complete recovery of the magnetite was realized under all operating conditions evaluated in the test program. As such, excellent magnetite recovery was achieved at volumetric capacities up to 12.8 gallons/minute/linear ft of drum width.

Table 5.2 Magnetite recovery results obtained from the rougher-only test program performed on the Eriez wet drum separator.

Test Number	Feed Solids Content (% by wght)	Feed Flow Rate (gpm)	Magnetic Field (gauss)	Magnetics Content (%)		Magnetics Recovery (%)
				Mag Stream	Non-Mag Stream	
1	30	2	1000	97.01	0.15	99.99
2			1100	97.69	0.08	99.99
3		5	1000	97.91	0.29	99.98
4			1100	98.03	0.51	99.96
5		8	1000	97.11	0.58	99.96
6			1100	97.24	0.73	99.95
7	20	2	1000	98.09	0.17	99.98
8			1100	98.89	0.12	99.98
9		5	1000	98.42	0.01	100.00
10			1100	98.75	0.01	100.00
11		8	1000	98.78	0.16	99.98
12			1100	98.84	0.34	99.95
13	10	2	1000	99.26	0.34	99.96
14			1100	99.30	0.11	99.99
15		5	1000	98.99	0.33	99.96
16			1100	99.00	0.01	100.00
17		8	1000	99.11	0.22	99.97
18			1100	99.11	0.01	100.00

On the other hand, the amount of non-magnetic material reporting to the magnetic overflow stream varied significantly over the range of operating parameter values tested as indicated by the data in Table 5.2. The most significant effect was realized by a change in feed solids content, whereby high contents enhance particle entrapment conditions within the magnetic material reporting to the overflow stream. As shown in Table 5.3, greater than 20% of the non-magnetic material in the feed was by-passed to the overflow at a solids content of 30% by weight. By reducing the feed solids content to 10% by weight, the recovery rate reduced to about 6%. Increasing the magnetic field also slightly reduced the recovery rate. The significance of the non-magnetic material reporting to the high density magnetic stream is the potential for destabilization of the medium over a period of circuit operating time.

Since nearly complete magnetite recovery was achieved in a single rougher stage treatment, a test program to determine the benefits of using a scavenger stage was not performed.

Table 5.3 Recovery of the non-magnetic material to the magnetic process stream in the rougher-only test program involving the Eriez wet drum separator.

Test Number	Feed Solids Content (% by wght)	Feed Volumetric Flow Rate (gpm)	Magnetic Field (gauss)	Magnetic Product Stream		
				Non-Mag Content (%)	Non-Mag Ash (%)	Non-Mag Recovery (%)
1	30	2	1000	2.99	17.08	22.72
2			1100	2.31	15.02	17.37
3		5	1000	2.09	14.60	15.73
4			1100	1.97	16.10	14.78
5		8	1000	2.89	16.06	21.90
6			1100	2.76	23.05	20.85
7	20	2	1000	1.91	11.17	14.33
8			1100	1.11	16.47	8.29
9		5	1000	1.58	20.72	11.85
10			1100	1.25	18.43	9.30
11		8	1000	1.22	17.08	9.08
12			1100	1.16	15.42	8.60
13	10	2	1000	0.74	9.53	5.47
14			1100	0.70	9.91	5.18
15		5	1000	1.01	13.73	7.48
16			1100	1.00	13.55	7.40
17		8	1000	0.89	13.54	6.60
18			1100	0.89	13.42	6.58

Final Clean Coal Production

The objective of the magnetite recovery system is to recover the magnetite and to generate a final clean coal product. Table 5.4 indicates that the ability to achieve a clean coal product in the +325 mesh fraction is dependent on the operating parameter values of the wet drum separator. Ash contents from 9.44% to 20.66% were obtained from the +325 mesh material collected from the wet drum underflow stream. Low ash contents were produced under conditions that also reduced the amount of +325 mesh material in the subject process stream. This trend likely indicates a density separation among the non-magnetic particles in the medium within the drum separator vessel.

Table 5.4 Composition of the material collected in the non-magnetic underflow stream of the wet drum magnetic separator treating the Falcon dense medium product.

Test Number	+325 Mesh Fraction		-325 Mesh Fraction	
	Weight (%)	Ash (%)	Weight (%)	Ash (%)
1	39.24	10.52	60.76	43.74
2	30.11	9.44	69.89	42.73
3	49.39	18.48	50.61	46.74
4	47.49	15.53	52.51	46.59
5	49.83	18.13	50.17	46.49
6	50.55	17.64	49.45	47.09
7	45.37	11.05	54.63	44.72
8	47.50	12.88	52.50	44.9
9	53.60	19.61	46.40	47.66
10	51.45	16.57	48.55	47.07
11	52.81	18.33	47.19	46.99
12	48.66	18.11	51.34	46.97
13	44.25	11.62	55.75	44.89
14	53.42	13.53	46.58	45.75
15	54.46	20.66	45.54	48.38
16	53.12	18.04	46.88	47.63
17	56.56	18.82	43.44	47.28
18	53.19	18.62	46.81	46.59

It is apparent from Figures 5.4 and 5.5 that a low volumetric feed flow rate of 2 gallons/min is required to produce sufficiently low product ash content values below 11%. Lower ash contents were also realized from the use of high feed ash contents, which, as reported earlier, causes a corresponding increase in the amount of contaminants in the magnetite recirculation stream. The ability to provide a high quality product is enhanced by increasing the magnetic field strength. The high field strength causes a greater magnetic particle density near the drum surface which results in the release of non-magnetic particles and thus a reduction in entrapped, by-pass material.

Figure 5.4 Effects of feed volumetric flow rate and solid concentration on the +325 mesh ash content in the underflow stream of the wet drum separator using a field strength of 1000 gauss.

Figure 5.5 Effects of feed volumetric flow rate and solid concentration on the +325 mesh ash content in the underflow stream of the wet drum separator using a field strength of 1100 gauss.

In summary, the ability to produce a low ash content, clean coal product is enhanced by a low. However, the necessity of the low feed rates and high solid contents is a function of the quality of the +325 mesh, non-magnetic material produced from the Falcon dense medium process.

Falcon Tailings Treatment

The amount of magnetic material in the tailings stream collected from the Falcon dense medium process was determined to be 94.97%. The ash content of the non-magnetic portion of the tailings material was 58.66%. Due to the small sample size, the number of open circuit, continuous tests was restricted to four.

As shown in Table 5.5, the wet drum separator recovered nearly all of the magnetite with a single stage of treatment. The final tailings of the Falcon dense medium process would be the +65 mesh particle size fraction obtained from a screen and the underflow of the wet drum magnetic separator. In the tests performed on the tailings, the ash content of the material reporting to the underflow of the wet drum ranged from 45% to 50%.

Table 5.5 Magnetite recovery and non-magnetite material composition obtained from the treatment of the Falcon tailings stream material.

Feed Solids Content (% by wght)	Magnetic Field (gauss)	Mag Product Magnetic Content (%)	Non-Mag Product Stream	
			Magnetic Content (%)	Non-Magnetic Ash Content (%)
20	1000	99.66	0	49.86
20	1100	99.67	0	49.69
10	1000	99.90	0	46.92
10	1100	99.92	0	45.59

SUMMARY AND CONCLUSIONS

A test program was conducted to evaluate the feasibility of recovering the magnetite used in the dense medium process involving the Falcon concentrator. In addition, the operating conditions required to produce a final clean coal product from the Falcon product stream material was investigated. Prior to the magnetic separation process, the Falcon product was screened at 65 mesh to remove the coarse material that is typically lost to the magnetic process stream due to entrapment. A single rougher treatment stage was studied in a series of 18 experiments to quantify operating parameter effects and optimize magnetite recovery using an Eriez L-8 laboratory wet drum unit. Conclusions derived from the test program can be summarized as follows:

1. A single rougher stage treatment using the wet drum magnetic separator was found to recover nearly 100% of the magnetite over the entire range of operating parameter values studied. As such, a scavenging stage is not required. Successful

magnetite recovery was obtained at volumetric capacities of 12.8 gallons/min/linear foot of drum width.

2. The amount of non-magnetic material reporting to the magnetic overflow process stream of the drum separator was found to significantly increase with elevated feed solid contents. The recovery of the material occurs by entrapment and potentially causes destabilization of the medium suspension over a period of operation time.
3. Volumetric feed flow rates significantly affected the ability to minimize the product ash content of the +325 mesh particle size fraction in the non-magnetic underflow stream of the drum separator. The production of ash contents below 10% required the lowest feed rate tested (2 gallons/min), an elevated feed solids content (30%) and the higher magnetic field strength (1100 gauss). Although the parametric effects remain unchanged, the absolute product ash content values are a function of the magnitude of cleaning achieved by the Falcon Concentrator.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the outcomes of the investigation, suggestions for future work include:

1. A study to evaluate methods needed to reduce the recovery of the non-magnetics into the overflow product stream of the drum separator. A cleaner stage would require the addition of a significant amount of water to dilute and disperse the magnetic material. This would increase cost significantly through the need of additional magnetic separator and the additional water.
2. Evaluation of a continuously operating circuit in conjunction with the Falcon Concentrator process and a dense medium control system to validate the findings of this investigation.

ACKNOWLEDGEMENTS

In addition to the funding support by the U. S. Department of Energy, the principal investigator greatly appreciates the support provided by Eriez Inc through the use of the wet drum magnetic separator and the technical assistance. Sincere gratitude is also expressed toward Ahmet Ozsever who set up the experiment, assisted in conducting the test program and performed all sample analyses.

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