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TECHNICAL REPORT
March 1, 1994 through May 31, 1994

Project Title: **A COMPARISON STUDY OF COLUMN FLOTATION
TECHNOLOGIES FOR CLEANING ILLINOIS COAL**

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ABSTRACT

The objectives of this research project are to optimize the performance of six commercially available column technologies for the treatment of Illinois Basin coal fines and to compare their performance on the basis of the recovery-grade curve and column throughput capacity. During the previous reporting period, characterization of an Illinois No. 5 flotation feed sample was completed and tests on the Jameson Cell were initiated.

During this reporting period, parametric studies using a Box-Behnken test design were conducted on the Jameson Cell, Packed-Column, and the Microcel. The results obtained from all three flotation technologies compared well with release analysis data. Excellent ash rejections of more than 85% were achieved by each flotation technology. However, for the test conditions used in this investigation, relatively low combustible recovery values were obtained from the Jameson Cell and the Packed-Column due to carrying capacity limitations. During the next reporting period, lower feed rates will be tested for these two technologies in an effort to improve recovery. Empirical models developed from the parametric studies will be used to predict the optimum operating parameter values. These optimum values will be used to obtain the best possible separation efficiency and maximum throughput for each flotation technology.

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EXECUTIVE SUMMARY

Column flotation achieves superior cleaning of fine coal as compared to conventional flotation due to its ability to support a large froth depth and the use of wash water in the froth zone which allow removal of entrained impurities from the froth. In addition, the external bubble generators used in column flotation produces smaller bubbles than conventional flotation which results in an increase in the rate of coal recovery from the pulp. Utilizing these basic principles, several column technologies have been developed which produce a cleaner coal product with greater recovery values than those achieved by conventional flotation cells.

A significant difference between the column technologies is the mechanism by which the microbubbles are produced. For a given aeration rate, these bubble generators differ in the size and the uniformity of the bubble produced and, thus, in the amount of bubble surface area available for the capture of coal particles. Some columns also differ with respect to the kind of environment in which bubble-particle collisions occur. For example, one technology utilizes a complete froth column to improve the chances of bubble-particle attachment. Other columns utilize packing or baffles to reduce turbulence, thereby, decreasing the probability of a particle escaping without bubble contact. The use of self-induced air and the generation of uniform microbubbles are novel concepts of other column technologies.

Several flotation columns have been tested on an individual basis for the treatment of Illinois Basin coal fines. However, these studies were not conducted on the same coal sample and under similar operating conditions. Thus, meaningful performance comparisons between the columns cannot be extracted from the experimental data. Therefore, in this study, six commercially available column technologies will be tested "head-to-head" using the same Illinois Basin fine coal slurry. These columns will include the *Flotaire* column, the *Jameson* cell, the *Microcel*TM column, the *Canadian* column, the *Packed*-column, and the *Turboair* column.

This research project will be conducted in two phases. In the first phase, the objective will be to optimize the critical operating parameters associated with each flotation column. A flotation feed coal slurry collected from a local coal preparation plant treating Illinois No. 5 seam coal will be used as the feed for these tests. The operating parameters to be optimized will include feed rate, aeration rate, frother concentration, and wash water rate. The optimized parameter values will be used in the second phase to create the ultimate recovery-grade curve and the maximum throughput capacity for each column technology. The results from the second phase will be used to compare the performance of the different column technologies.

The objectives of this project are: (1) to optimize the values of the critical operating variables associated with 6 commercially available flotation columns for the treatment of Illinois Basin coal fines, (2) to compare the column technologies on the basis of the recovery-grade curve, and (3) to determine and contrast the throughput capacities of each column flotation technology.

During this reporting period, parametric studies using a Box-Behnken statistical test design were conducted on the Jameson Cell, Packed-Column, and the Microcel. The Jameson Cell is a 6-inch diameter flotation cell that is 4 feet in height and is equipped with a 1.25-inch diameter downcomer. The Packed-Column and the Microcel have internal diameters of 4 and 2 inches, respectively, and are both 16 feet in height. All tests were conducted using one cleaning stage only. A polyglycol (Dowfroth M150) was the frother and kerosene was the collector used in all experiments. A time period of three volumetric retention times was allowed prior to sample collection of the feed, product, and tailing streams to ensure steady-state conditions. The samples were filtered, dried and weighed, and then analyzed for ash and total sulfur content using standard ASTM procedures.

The Jameson Cell achieved a separation performance in a single stage of treatment comparable to the release analysis data with a single stage of treatment. The ash content of the Illinois No. 5 coal sample was reduced from about 30% to 5% while maintaining a combustible recovery value of 80%. The maximum separation efficiency obtained using the Jameson Cell was approximately 70% compared to an optimum value of 80% predicted by the release analysis data. Total sulfur was decreased from approximately 1.4% to 1.2%, resulting in a total sulfur rejection of more than 40%. Combustible recovery values were maximized at about 80%. It is believed that this finding was a result of carrying capacity limitations. Therefore, higher recovery values should be achievable by reducing the feed rate from the value of 600 grams/minute used in the tests as suggested by the respective vender.

The results from the parametric study conducted on the Jameson Cell indicated that frother dosage and froth height were the critical parameters affecting all the response variables which include combustible recovery, product ash content and separation efficiency. The effect of operating parameters such as, superficial gas rate and wash water rate were, on the other hand, found to be statistically insignificant in the range of values studied. Based on the empirical models obtained from the parametric study, tests during the next reporting period will be conducted at a reduced froth height (18 cm) and an increased frother concentration (26 ppm) in an effort to achieve higher combustible recovery values and an optimum separation performance. In addition, mass feed rates will be reduced since carrying capacity limitations were

believed to restrict recovery values.

The Packed-Column produced results comparable to the release analysis data as well. The ash content was typically reduced from about 30% to 3% which corresponds to an ash rejection of more than 95%. Total sulfur was also decreased significantly from 1.4% to 1.0% providing a 60% sulfur rejection. Combustible recovery values, however, were found to be relatively low as indicated by a maximum value of 73%. This is believed to be due to carrying capacity limitations. The Packed-Column tests were conducted at a mass feed rate of 200 grams/minute as suggested by the inventor, Dr. D. Yang. However, visual observations by the principal investigators and test results found that feed rates lower than 100 grams/minute should have been used to achieve high combustible recovery values. A range of feed rates from 40 to 100 grams/minute will be tested during the next reporting period.

The results from the parametric study on the Packed-Column indicated that superficial gas velocity and froth depth were the critical parameters affecting the response variables. To achieve optimum performance, future tests will be conducted at 1.8-2.1 meters of froth depth, a gas velocity of 4.6 cm/sec, a wash water rate of 0.75 liters/minute and a frother concentration of 36 ppm.

Results obtained from the Microcel flotation column also compared very well with those obtained from release analysis. A 90% ash rejection was achieved with a combustible recovery of 90%, resulting in an excellent separation efficiency of approximately 80%. This separation resulted in a final concentrate containing about 5% ash.

Optimum parameter values were found to be 2.1 cm/sec for superficial gas rate, 25 ppm for frother concentration, and 500 ml/min for wash water. Tests will be conducted over a wide range in feed rates during the next reporting period using these optimum parameter values to establish the best possible recovery-grade relationship and maximum throughput.

During the next reporting period, the optimization experimental program will be conducted on the three remaining column flotation technologies. A comparison of the technologies will be conducted once the optimum conditions have been established for all the columns.

OBJECTIVES

The goal of this research project is to evaluate and compare the effectiveness of six commercially-available flotation column technologies for the cleaning of Illinois Basin coal fines. The specific objectives of the proposed work are:

1. To optimize the values of the critical operating variables associated with 6 commercially available flotation columns for the treatment of Illinois Basin coal fines;
2. To compare the recovery-grade relationships generated from the treatment of Illinois basin flotation feed coal slurries using a number of different column technologies;
3. To determine and contrast the throughput capacities of the column flotation technologies for the treatment of Illinois basin coal fines.

The flotation technologies that will be evaluated in this study will include the Microcel™ Column, the Turboair Column, the Flotaire Column, the Canadian Column, the Jameson Cell, and the Packed-Column. The specific questions to be answered by this investigation include 1) Do all flotation columns produce the same recovery-grade curve when properly operated?; 2) Does the method of bubble generation, or the type of bubble-particle attachment zone (liquid or froth) affect flotation kinetics so as to change the device throughput or reagent consumption?

To achieve the project objectives, the work has been divided into six distinctly different tasks which are briefly described in the following paragraphs:

Task 1 - Sample Acquisition: The coal samples that will be used in this investigation are flotation feed coal slurries collected from two preparation plants in which one treats Illinois No. 5 seam coal and the other treats Illinois No. 6 seam coal.

Task 2 - Sample Characterization: Both the Illinois No. 5 and No. 6 flotation feed samples will be analyzed for their solids content, particle size distribution, proximate analysis, total and pyritic sulfur content, and BTU content. In addition, a release analysis will be conducted on each sample to obtain the ultimate recovery-product ash and recovery-product sulfur content curves.

Task 3 - Operating Parameter Optimization: An experimental program based on a Box-Behnken test design will be conducted on each flotation column using the Illinois No. 5 coal sample

as the feed. The test results will be used to develop empirical relationships which describe the effect of the critical operating parameters on the process response variables. The operating variables will be optimized using these empirical expressions.

Task 4 - Recovery/Grade Testing: To determine the ultimate recovery-grade curve that each column is capable of achieving, tests will be conducted using the optimum operating parameter values corresponding to the maximum separation efficiency value as determined in Task 3. The recovery-grade curves will be generated by performing a series of tests over a range of feed rate values. After conducting these tests on both the Illinois No. 5 and No. 6 coal samples, the recovery-grade curves will be compared with those obtained by release analysis in Task 2.

Task 5 - Throughput Capacity Testing: Tests will be conducted on each column at three different feed rates. The feed rate values will be determined by selecting three yield values, which will be the same for each column, and calculating the corresponding feed rates from the empirical yield expression developed in Task 3. This will validate the empirical equation. From this data, throughput capacity values will be determined for each column and compared.

Task 6 - Data Analysis and Review: Upon completion of Tasks 1 through 5, the project data will be synthesized into a preliminary report and distributed to the column vendors for their comments and suggestions for future work.

INTRODUCTION AND BACKGROUND

Background

In mineral processing, froth flotation is regarded as the best available technique for separating fine particles. Unfortunately, conventional flotation machines become ineffective when the particle size is very small or when the flotation pulp contains a large amount of finely dispersed clay or silicious gangue. Small hydrophobic particles, such as fine coal, have a low probability of collision with air bubbles, resulting in a low recovery. In addition, fine mineral matter particles are entrained into the froth product along with the process water, resulting in poor selectivity. When processing fine particles, such as a typical flotation feed, both of these problems have to be resolved to obtain the desired separation performance.

A solution to the entrainment problem is the use of flotation columns. In such devices, wash water being added to the froth phase creates a net downward flow of water, called positive

bias, so that the flow of pulp water to the froth phase can be prevented. As a result, entrained gangue particles entering the flotation froth are rejected back into the pulp phase. Therefore, columns are useful for obtaining high product quality.

Several flotation columns have been developed in recent years to take advantage of the facts that: (1) small bubbles can increase the recovery of the desirable component and (2) the use of wash water can produce cleaner products. The main differences between the various column technologies is the method of bubble generation and, in some cases, the nature of the bubble-particle attachment zone. The various commercially available columns can be described as follows:

1. The *Flotaire (Deister) column*, a technology patented and marketed by Deister Company, Inc., uses porous venturi tubes similar to the one shown in Figure 1a. The fast moving fluid inside the smaller tubing, which is made of porous stone, removes bubbles from their nucleation sites before they grow in size.
2. The *Turboair column*, a unit developed by the U.S. Bureau of Mines, utilizes a bubble generator that disperses pressurized air in a packed bed of glass beads prior to passing the air/water mixture through a fine orifice at high speed. Figure 1b shows the aeration chamber, which is filled with glass beads. The *Cominco* sparging system is similar to the U.S. Bureau of Mines design except that the pressurized air and water are mixed at a T-joint rather than in the packed bed of glass beads. Also, the wear of the orifice is minimized by carbide inserts. The *Turboair* column is presently being marketed by Control International, Inc, and Pyramid Resources, Inc..
3. The *Microcel™ column*, a unit developed by the Virginia Center for Coal and Mineral Processing, uses an in-line static mixer for bubble generation (Figure 1c). Aerated slurry is passed through the mixer to create a high degree of turbulence for bubble generation. The column pulp is withdrawn through an inverted pump suction port at the bottom of the cell. The centrifugal pump discharges the pulp to a distributor ring which, in turn, feeds several spargers (i.e., static mixers). Each sparger is individually aerated by an air distribution ring. The *Microcel* column is presently being marketed by Control International, Inc., and ICF Kaiser Engineers.

a) Porous Venturi Tube (*Flotaire* Column)

b) Turbo Generator (*Turboair* Column)

c) In-Line Mixer (*Microcel*™)

d) Internal Sparger (*Canadian* Column)

Figure 1. Schematic representations of different microbubble generators.

4. The *Canadian column*, the original conventional-type column (Figure 2a) and commercially marketed by the Column Flotation Company of Canada, utilizes internal spargers made from perforated pipe that is usually covered with perforated rubber. A water/frother mixture and air are passed through the perforated sparger to produce the bubbles (Figure 1d). The sparger system used in the *Ken-Flote* column, which was developed at the University of Kentucky, is similar to the Canadian Column in that air and a water/frother mixture are forced through a porous frit to generate the microbubbles.
5. The *Jameson cell* is a non-conventional column which is divided into two zones, one for fast bubble-particle contacting and one for concentrate cleaning. Bubble-particle contacting in this column takes place in a downcomer where the feed slurry and air are intimately mixed. This is achieved by a high pressure feed which is forced through a small orifice in the downcomer. The jet action of the feed into the downcomer passes an opening to the atmosphere that naturally draws air into the tubes and shears the air to produce fine bubbles (Figure 2b). The concentrate laden froth is released at the bottom of the downcomer into a column where the resulting froth layer is cleaned by a countercurrent flow of wash water. The unique aspect of the Jameson cell as compared to the other flotation columns is that the air is self-inducting. The Jameson cell is patented and internationally marketed by MIM Limited.
6. The *Packed (or Static) column*, developed at the Michigan Technological University, incorporates a packed-bed column design to provide small flow passages for enhanced bubble-particle attachment (Figure 2c). The packing in the column is a stack of corrugated plates. Compressed air enters in the bottom of the column and the bubbles are generated by bubble shear through the internal packing. An additional advantage of this column is that the packing tends to provide greater support for the froth so that a complete froth column can be utilized. The Packed-column is marketed exclusively by Groupe Laperriere & Verreault Ontario Inc..

A common feature of all of the flotation columns is that generation of small bubbles relies on the shear rate of the fluid at the bubble nucleation site. In general, bubble size can be reduced either by increasing the *shear rate*, which can be accomplished by increasing the energy dissipation in the system, or by reducing the *surface tension*, which can be

a)

b)

c)

Figure 2. Schematic of a a) conventional flotation column (Dobby and Finch (1990), b) Jameson cell (Kennedy, 1990), and a c) Packed-column (Yang, 1988).

accomplished by adding more frother. The addition of larger amounts of frother, however, can be detrimental to selectivity as a result of increased water recovery from the pulp to the froth. Reducing bubble size by increasing the shear rate is a better choice in terms of selectivity, but this alternative could result in a somewhat higher energy consumption.

Several column sparging systems rely on the addition of external water to the bubble generation circuit to increase the amount of shear (i.e., Canadian, Turboair, and Deister). However, the bubble generation water can significantly reduce the column retention time. This requires additional cell volume to maintain the same retention time. Other columns, such as the Packed, Jameson and Microcel columns, do not require the extra water for bubble generation and, thus, should require less cell volume to treat a given throughput.

Due to the production of larger bubbles by some sparger systems, a few of the column technologies require high superficial gas rates (V_g) to achieve the desired recovery rate. However, the amount of air that one can inject into a column is limited by a transition from uniform bubbly flow to churn-turbulent flow. The flotation rate at this transitional V_g value can be further improved by the addition of a larger concentration of frother to decrease the bubble size. However, past research has found that frother concentrations greater than 20 ppm have little effect on bubble size (Flint et al., 1988). Therefore, the throughput capacity and recovery values that flotation columns are capable of achieving are limited by the number and size of the bubbles produced by their bubble generation system:

EXPERIMENTAL PROCEDURES

Operating Parameter Optimization: Exploratory tests were conducted on the Jameson Cell, Packed-Column, and Microcel to determine the range of parameter values to be used in the optimization experimental program. All tests were conducted using the Illinois No. 5 flotation feed sample. Prior to each set of experiments, a complete 55-gallon drum of sample was placed into a feed sump equipped with baffles, mixer, and a recirculating pump which were used to ensure complete dispersion of the sample. The collector was added at a concentration of 0.5kg/ton to the feed slurry and a period of 10 minutes was allowed for conditioning before the start of the experiments.

The operating parameters considered as part of the parametric study for the Jameson Cell and their respective ranges of values are as follows:

Frother Concentration:	15 - 25 ppm
Superficial Gas Rate:	0.9 - 1.2 cm/sec
Wash Water Rate:	1.9 - 3.8 liters/min
Froth Depth:	20 - 45 cm

Feed rate in the Jameson Cell was maintained at a mass flow rate of 600 grams/min to ensure a feed pressure of 20 psi as suggested by the vendor. The tests were conducted in a single stage and without the use of a crowder. Thus, a change in the superficial gas rate also varies the air-to-pulp ratio.

The operating parameter values used in the parametric study of the Packed-Column and their respective range of values are as follows:

Aeration Rate:	3.4 - 4.6 cm/sec
Frother Concentration:	125 - 175 μ l/min
Froth Height:	1.8 - 3.0 meters
Wash Water Rate:	0.8 - 1.6 liters/min

Feed rate was maintained at a constant value of 200 grams/min as recommended by the vendor. Feed air pressure was kept constant at 30 psi. The ranges in parameter values were obtained from the vendor, publications, and exploratory tests. It was the goal of the principal investigators to operate the column under bubbly-flow conditions as opposed to churn-flow or turbulent conditions.

The operating parameters and their respective range of values selected for the Microcel are as follows:

Aeration Rate:	1.5 - 2.2 cm/sec
Frother Concentration:	20 - 30 ppm
Mass Feed Rate:	18 - 30 gms/min
Wash Water Rate:	300 - 700 ml/min

Froth height was held constant at 38 cm and the wash water was added approximately 12 cm from the top of the cell. Air feed pressure was 36 psi.

A time period equal to three volumetric retention times was allowed prior to the collection of timed-samples from the feed, product, and tailing streams. The samples were dried, filtered and weighed, and then analyzed for ash and total sulfur content.

A Box-Behnken test design was used for the parametric study on each flotation technology. As a result, a four-parameter experimental program required 27 experiments to be conducted on each flotation device. The experimental data were entered into Design-Expert, a commercially-available statistical package, to develop empirical models describing the response variables as a function of the operating parameters. Using

the empirical models, the optimum operating variables were obtained.

RESULTS AND DISCUSSION

Jameson Cell:

The results obtained from the 27 tests conducted in the parametric study are shown in Table 1. Product ash values ranged from 4.08% to 6.84% while the total sulfur content of the product varied from 1.17% to 1.41%. The ash content of the tailings varied from 46.7% to 67.4%. Using these results, combustible recovery values were found to range from 51% to 81% while achieving ash rejections between 85% to 95% as shown by the results in Table 2. Separation efficiency values ranged from 45% to 70%.

These values were entered into the Design-Expert package to obtain the empirical expressions for combustible recovery, product ash and total sulfur rejection, and separation efficiency. An ANOVA analysis of the data found that the critical parameters for all response variables are froth height and frother dosage. Surprisingly, superficial gas rate and wash water rate were found to have an insignificant effect on the response variables over the range of values studied.

The empirical models that were developed show that the best possible separation performance may be achieved by increasing the frother dosage to 26 ppm and decreasing the froth height to 17.5 cm while maintaining the superficial gas rate and wash water rate at 0.9 cm/sec and 1.8 liters/min, respectively.

Figure 3(a) - (b) show the combustible recovery values plotted versus ash rejection and total sulfur rejection, respectively, for both release analysis and Jameson Cell results. As shown, the Jameson Cell produced results comparable to the release analysis data, which represents the best possible performance that can be achieved by a flotation process. It is believed that by decreasing the feed rate while holding all other parameter values constant will result in a shift toward higher recovery values along the release curve.

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Table 1. Ash and total sulfur contents of the samples collected from a parametric study of the Jameson Cell.

Test #	Ash Content (%)			Total Sulfur Content (%)		
	Feed	Product	Tailing	Feed	Product	Tailing
1	30.40	5.29	57.68	1.44	1.31	1.59
2	27.79	4.57	63.16	1.38	1.26	1.56
3	27.81	5.14	63.70	1.34	1.30	1.40
4	30.61	6.68	67.27	1.37	1.32	1.45
5	30.58	5.01	59.42	1.38	1.31	1.44
6	31.97	5.05	54.90	1.27	1.23	1.29
7	31.98	4.96	58.36	1.24	1.19	1.29
8	27.59	5.27	57.33	1.32	1.23	1.43
9	30.66	5.36	59.19	1.25	1.25	1.24
10	30.51	4.22	57.88	1.26	1.17	1.36
11	30.98	4.33	50.11	1.45	1.17	1.64
12	30.75	4.69	52.47	1.41	1.18	1.61
13	32.37	5.56	65.58	1.35	1.31	1.41
14	32.35	6.68	67.33	1.35	1.34	1.37
15	32.37	4.48	52.38	1.31	1.28	1.34
16	28.41	5.46	50.26	1.33	1.23	1.42
17	28.51	6.84	62.98	1.28	1.20	1.41
18	28.19	5.68	60.76	1.37	1.19	1.62
19	28.35	5.15	48.62	1.43	1.31	1.53
20	28.34	5.60	57.29	1.42	1.31	1.55
21	29.50	4.08	49.59	1.42	1.25	1.56
22	29.05	5.65	64.11	1.59	1.41	1.87
23	28.44	6.05	63.51	1.47	1.36	1.65
24	28.58	6.14	57.85	1.39	1.36	1.43
25	30.34	4.26	46.67	1.32	1.23	1.37
26	30.34	4.95	54.55	1.32	1.28	1.37
27	30.33	4.69	45.59	1.32	1.24	1.36

Table 2. Calculated separation performance data obtained from the parametric study of the Jameson Cell.

Test #	Yield (%)	Combustible Recovery (%)	Ash Rejection (%)	T. Sulfur Rejection (%)	Separation Efficiency (%)
1	52.07	70.86	90.94	52.77	61.79
2	60.37	79.78	90.07	44.92	69.85
3	61.29	80.53	88.67	40.47	69.21
4	60.51	81.37	86.80	41.82	68.17
5	53.00	72.52	91.32	49.36	63.84
6	46.00	64.20	92.73	55.35	56.93
7	49.40	69.02	92.34	52.62	61.36
8	57.14	74.75	89.08	46.58	63.82
9	53.00	72.34	90.74	46.74	63.08
10	51.00	70.30	92.95	52.76	63.24
11	41.78	57.92	94.17	66.14	52.08
12	45.46	62.57	93.07	62.15	55.64
13	55.34	77.27	90.50	46.37	67.76
14	57.67	79.56	88.09	42.87	67.65
15	41.77	59.00	94.22	59.40	53.22
16	48.78	64.42	90.62	54.90	55.04
17	61.40	80.01	85.26	42.39	65.27
18	59.13	77.67	88.09	48.35	65.76
19	46.62	61.71	91.53	57.30	53.25
20	56.00	73.77	88.94	48.36	62.71
21	44.15	60.07	93.90	61.23	53.96
22	59.98	79.76	88.33	47.03	68.08
23	61.03	80.12	87.03	43.71	67.15
24	56.60	74.39	87.84	44.71	62.23
25	38.50	52.91	94.59	63.92	47.51
26	48.80	66.59	92.04	52.98	58.63
27	37.30	51.03	94.23	64.74	45.26

a)

b)

Figure 3. A comparison between the results obtained from the Jameson Cell and release analysis (Feed rate = 600 g/m, Wash water = 1.9 - 3.8 l/m).

Packed-Column:

The results obtained from the parametric tests conducted on the Packed-Column are shown in Tables 3 and 4. Product ash values as low as 2.58% was realized while the maximum ash content was only 7.1%. This resulted in a range of ash rejections between 85% and 95%. Substantial reductions in total sulfur content was also obtained as indicated by a decrease in sulfur content from 1.4% to 1.0%. As a result of the extremely high product quality, relatively low combustible recovery values were obtained with a maximum value being 73%.

An ANOVA analysis was also conducted on these results and found aeration rate and froth height to be significant operating parameters. Frother dosage and wash water were found to have insignificant effect on the response variables in the range of values tested.

Optimization of the operating parameters using empirical models found that the maximum separation efficiency of more than 75% is achievable using the Packed-Column. To achieve optimum results, an aeration rate of 4.4 cm/sec and a froth height of 1.9 meters should be used while maintaining the frother concentration at 36 ppm and the wash water at 0.8 liters/min. To achieve high recovery values, feed rates less than 100 gms/min must be used.

Figures 4 (a) and (b) show a comparison of the results obtained from the Packed-Column and the release analysis with respect to ash and total sulfur rejection. As shown, the Packed-Column is able to produce results that are comparable to those generated by release analysis.

Microcel:

The ash contents of the samples collected from the Microcel tests are shown in Table 5. Total sulfur values were not available at the time of report preparation. As shown, product ash values ranging from 3.3% to 9.0% was obtained while also producing tailing ash content values greater than 75%. As a result, very high combustible recovery values were achieved which resulted in separation efficiency values as high as 80% which is approximately equal to the maximum value predicted from the release analysis results.

At this time, analysis of the results using Design-Expert package has not been conducted. However, as shown by the comparison in Figure 5 between the Microcel and release analyses results, most of the experimental operating conditions resulted in near perfect separation performance.

Table 3. Ash and total sulfur contents of the samples collected from a parametric study of the Packed-Column.

Test #	Ash Content (%)			Total Sulfur Content (%)		
	Feed	Product	Tailing	Feed	Product	Tailing
1	31.41	5.43	60.24	1.28	1.25	1.32
2	31.49	7.07	54.95	1.29	1.27	1.30
3	31.44	4.85	57.78	1.28	1.24	1.31
4	32.53	3.21	55.09	1.27	1.05	1.42
5	32.89	5.29	62.03	1.30	1.27	1.32
6	32.34	2.58	50.69	1.26	0.94	1.47
7	32.15	2.84	43.79	1.28	0.95	1.41
8	32.72	4.19	59.09	1.27	1.16	1.37
9	27.53	3.88	44.94	1.44	1.14	1.66
10	27.69	7.10	54.47	1.42	1.31	1.56
11	27.57	3.73	45.17	1.43	1.08	1.69
12	27.65	3.78	47.81	1.42	1.21	1.17
13	27.56	5.55	44.56	1.46	1.22	1.58
14	29.22	4.06	48.42	1.44	1.16	1.66
15	29.35	3.48	47.84	1.42	1.09	1.66
16	29.28	3.56	44.87	1.43	1.02	1.69
17	29.27	3.17	44.28	1.44	1.05	1.66
18	29.56	2.85	42.46	1.39	0.98	1.59
19	29.49	3.65	48.41	1.40	1.04	1.66
20	31.11	3.89	47.72	1.33	1.06	1.06
21	31.24	5.04	57.17	1.32	1.21	1.21
22	31.27	4.81	57.32	1.31	1.17	1.17
23	31.15	4.83	57.49	1.37	1.24	1.24
24	31.13	7.38	59.27	1.38	1.27	1.27
25	31.18	5.87	52.50	1.37	1.22	1.22
26	31.13	5.12	59.93	1.35	1.26	1.26
27	31.23	4.00	51.31	1.38	1.15	1.15

Table 4. Calculated separation performance data obtained from the parametric study of the Packed-Column.

Test #	Yield (%)	Combustible Recovery (%)	Ash Rejection (%)	T. Sulfur Rejection (%)	Separation Efficiency (%)
1	52.60	72.52	90.91	48.63	63.43
2	49.00	66.47	88.99	51.76	55.46
3	49.76	69.06	92.32	51.45	61.39
4	43.49	62.38	95.71	64.11	58.09
5	51.36	72.48	91.74	49.55	64.22
6	38.14	54.92	96.96	71.55	51.88
7	28.42	40.70	97.49	78.94	38.19
8	48.03	68.40	93.85	56.13	62.25
9	42.41	56.24	94.02	66.55	50.26
10	56.54	72.63	85.50	47.69	58.13
11	42.47	56.45	94.25	68.00	50.70
12	45.79	60.90	93.73	60.83	54.63
13	43.58	56.82	91.23	63.49	48.04
14	43.28	58.67	93.99	65.12	52.65
15	41.68	56.95	95.05	68.11	52.00
16	37.74	51.46	95.41	73.16	46.88
17	36.51	49.98	96.05	73.41	46.03
18	32.57	44.92	96.86	77.05	41.78
19	42.27	57.76	94.77	68.47	52.53
20	37.90	52.87	95.26	69.72	48.13
21	49.74	68.69	91.98	54.52	60.67
22	49.61	68.71	92.36	55.52	61.07
23	50.02	69.14	92.24	54.77	61.38
24	54.23	72.93	87.14	50.36	60.08
25	45.72	62.54	91.39	59.13	53.93
26	52.55	72.39	91.35	50.73	63.74
27	42.44	59.25	94.56	64.77	53.81

a)

b)

Figure 4. A comparison between the results obtained from the Packed-Column and release analysis (Feed rate = 200 g/m, Wash water = 0.8 - 1.6 l/m).

Table 5. Ash contents of the samples collected from a parametric study of the Microcel.

Test #	Ash Content (%)		
	Feed	Product	Tails
1	30.87	5.21	79.55
2	30.87	3.92	70.57
3	31.13	4.59	75.46
4	29.73	5.73	83.23
5	30.87	3.90	75.41
6	29.73	8.45	86.47
7	31.13	5.47	82.88
8	31.13	5.30	81.07
9	30.87	4.52	75.27
10	30.87	4.84	77.49
11	31.13	8.96	86.44
12	31.13	6.65	85.53
13	31.13	3.29	82.16
14	31.13	6.4	85.75
15	29.73	16.74	81.78
16	31.13	4.70	78.57
17	29.73	6.78	81.28
18	31.13	6.61	83.90
19	29.73	6.38	83.58
20	31.13	4.71	80.72
21	31.13	6.92	86.76
22	31.13	6.5	86.7
23	31.13	6.71	86.71
24	31.13	5.88	81.16
25	29.73	7.06	85.3
26	31.13	5.54	83.16
27	31.13	6.16	84.36

Table 6. Calculated separation performance data obtained from the parametric study of the Microcel.

Test #	Yield (%)	Combustible Recovery (%)	Ash Rejection (%)	Separation Efficiency (%)
1	65.48	89.79	88.95	78.74
2	59.56	82.79	92.44	75.22
3	62.55	86.66	90.78	77.43
4	69.03	92.61	86.70	79.30
5	62.28	86.58	92.13	78.72
6	72.72	94.75	79.33	74.08
7	66.85	91.76	88.25	80.01
8	65.91	90.63	88.78	79.41
9	62.76	86.68	90.81	77.49
10	64.17	88.33	89.94	78.27
11	71.39	94.37	79.45	73.82
12	68.97	93.48	85.27	78.75
13	64.70	90.86	93.16	84.02
14	68.83	93.55	85.85	79.40
15	80.03	94.82	54.94	49.76
16	64.22	88.87	90.30	79.17
17	69.19	91.79	84.22	76.01
18	68.28	92.58	85.50	78.09
19	69.75	92.93	85.03	77.96
20	65.24	90.27	90.13	80.40
21	69.68	94.17	84.51	78.68
22	69.29	94.07	85.53	79.60
23	69.48	94.11	85.02	79.13
24	66.46	90.82	87.45	78.27
25	71.03	93.94	83.13	77.07
26	67.03	91.94	88.07	80.01
27	68.07	92.75	86.53	79.28

Figure 5. A comparison between the results obtained from the Microcel and release analysis on the basis of ash rejection (Feed rate = 18 - 30 g/m, Wash water = 300 - 700 ml/m).

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the results presented in this report:

Jameson Cell:

1. Jameson cell can achieve a separation performance comparable to the release analysis data. The ash content of the Illinois No. 5 coal sample was reduced from about 30% to 5% while maintaining a combustible recovery value of 80%. The maximum separation efficiency achieved by the Jameson Cell was about 70% compared to an optimum value of 80% predicted by the release analysis data. Total sulfur was decreased from approximately 1.4% to 1.2%, resulting in a total sulfur rejection of more than 40%.
2. Combustible recovery values were maximized at about 80%. It is believed that this finding was a result of carrying capacity limitations. Therefore, higher recovery values should be achievable by reducing the feed rate from the value of 600 grams/minute used in the tests as suggested

by the respective vender.

3. The parametric study using a Box-Behnken experimental design indicated that frother dosage and froth height were the critical parameters affecting all the response variables such as combustible recovery, product ash content and separation efficiency. The effect of operating parameters such as, superficial gas rate and ash water were, on the other hand, found to be statistically insignificant in the range of values studied.
4. Based on the empirical models obtained from the parametric study, tests during the next reporting period will be conducted at a reduced froth height (18 cm) and an increased frother concentration (26 ppm) in an effort to achieve higher combustible recovery values and an optimum separation performance. In addition, mass feed rates will be reduced since carrying capacity limitations were believed to restrict recovery values.

Packed-Flotation Column:

5. The Packed-Column was found to produce results comparable to the release analysis data. The ash content was typically reduced from about 30% to 3% which corresponds to an ash rejection of more than 95%. Total sulfur was also decreased significantly from 1.4% to 1.0% providing a 60% sulfur rejection.
6. Combustible recovery values, however, were found to be relatively low as indicated by a maximum value of 73%. This is believed to be due to carrying capacity limitations. The Packed-Column tests were conducted at a mass feed rate of 200 grams/minute as suggested by the inventor, Dr. D. Yang. However, visual observations by the principal investigators and test results found that feed rates lower than 100 grams/minute should have been used to achieve high combustible recovery values. A range of feed rates from 40 to 100 grams/minute will be tested during the next reporting period.
7. A parametric study found that superficial gas velocity and froth depth were the critical parameters affecting all of the response variables. To achieve optimum performance, future tests will be conducted at 1.8-2.1 meters of froth depth, a gas velocity of 4.6 cm/sec, a wash water rate of 0.75 liters/minute and a frother concentration of 36 ppm.

Microcel Flotation Column:

8. Results obtained from the Microcel flotation column compared very well with those obtained from release analysis. A 90% ash rejection was achieved with combustible recovery of 90%, resulting in an excellent separation efficiency of approximately 80%. This separation resulted in a final concentrate containing about 5% ash.
9. Optimum parameter values were found to be 2.1 cm/sec for superficial gas rate, 25 ppm for frother concentration, and 500 ml/min for wash water. Tests will be conducted over a wide range in feed rates during the next reporting period using these optimum parameter values to establish the best possible recovery-grade relationship and maximum throughput.

During the next reporting period, the optimization experimental program will be conducted on the three remaining column flotation technologies. A comparison of the technologies will be conducted once the optimum conditions have been established for all the columns.

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- Kennedy, A., 1990, "The Jameson Flotation Cell," *Mining Magazine*, October, pp. 281 - 285.
- Yang, D. C., 1988, "A New Packed-Column Flotation System," in Column Flotation '88', Proceedings of the Int. Symposium on Column Flotation, Phoenix, Arizona, Jan. 25 - 28, pp. 257 - 265.

PROJECT MANAGEMENT REPORT
March 1, 1994 through May 31, 1994

**Project Title: A Comparison Study of Column Flotation
Technologies for Cleaning Illinois Coal**

DOE Grant Number: DE-FC22-92PC92521 (Year 2)
ICCI Project Number: 93-1/5.1A-1P
Principal Investigator: R. Q. Honaker
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Southern Illinois University
at Carbondale
Other Investigator: B. C. Paul
Department of Mining Engineering
Southern Illinois University
at Carbondale
Project Manager: Ken Ho, Illinois Clean Coal
Institute

COMMENTS

Work on the column project is now moving very rapidly. The nonconventional column technologies requiring special operating procedures (Jameson Cell and Packed Column) as well as the Microcel have had parametric studies completed, leaving only columns that differ in bubble generation system alone to be finished by now experienced crews during the summer months. Most budget lines are very close to the projected levels. Travel is under budget since sample collection was charged by Physical Plant to another line. A budget adjustment request for this money has been submitted. Materials and supplies are over projection, but the column and centrifugal washing projects use common analysis and sample preparation labs, and lab consumables have been charged more frequently to the column project. The situation will adjust itself in the fourth quarter. Graduate student, Post Doc., and student labor have been higher than projected, effecting the fringe and labor costs. Internal reallocation of funds between members of the project research team will bring these lines into balance during the fourth quarter with few budget adjustments in the project. No financial or technical problems are anticipated for the project.

Projected and Estimated Expenditures by Quarter

Quarter*	Types of Cost	Direct Labor	Fringe Benefits	Materials & Supplies	Travel	Major Equipment	Other Direct Costs	Indirect Costs	Total
Sept. 1, 1993 to Nov. 30, 1993	Projected	7,642	609	2,375	400	9,600	2,850	2,348	25,824
	Estimated	4,500	686	7,560	27	8,352	2,000	2,312	25,437
Sept. 1, 1993 to Feb. 28, 1994	Projected	15,284	1,218	4,750	900	9,600	5,700	3,745	41,197
	Estimated	14,680	2,360	7,754	27	8,638	6,601	4,006	44,066
Sept. 1, 1993 to May 31, 1994	Projected	20,067	1,827	7,125	1,500	9,600	8,550	4,867	53,536
	Estimated	23,875	3,882	9,500	27	9,250	8,488	5,502	60,524
Sept. 1, 1993 to Aug. 31, 1994	Projected	39,363	5,490	9,500	2,000	9,600	11,400	7,735	85,088
	Estimated								

*Cumulative by Quarter

COSTS BY QUARTER**A Comparison Study of Column Flotation Technologies for
Cleaning Illinois Coal**

Cumulative \$
(thousands)

O = Projected Expenditures -----
Δ = Estimated Actual Expenditures _____

Total Illinois Clean Coal Institute Award \$85,088

SCHEDULE OF PROJECT MILESTONES

Milestones:

- A. Research assistants employed.
- B. Equipment ordered and received.
- C. Sample acquisition completed (Task 1).
- D. Sample characterization completed (Task 2).
- E. Operating parameter optimization finished (Task 3).
- F. Recovery/grade test program completed (Task 4).
- G. Throughput capacity tests completed (Task 5).
- H. Data analysis and review achieved (Task 6).
- I. Technical reports prepared and submitted.
- J. Project management reports prepared and submitted.

**DATE
FILMED**

10 / 5 / 94

END