TECHNICAL REPORT
September 1 through November 30, 1993

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

DOE Grant Number: DE-FC22-92PC92521 (Year 2)

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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. A statistically-designed experimental program will be conducted to optimize the critical operating performance values of each flotation column. The operating values suggested by the vendor will be used as the center point of the design. The ultimate recovery-grade curve and the maximum throughput capacity for each column will be determined by conducting further tests using the optimum operating parameter values.

During this reporting period, the flotation columns that were not already present were purchased and received. Installation of all the flotation columns was completed with the exception of the Packed-Column which is presently being mounted. A total of 25 fifty-five gallon drums of Illinois No. 5 flotation feed coal (-100 mesh) was collected at a local preparation plant to be used as the feed for the comparison tests. A complete characterization of this coal sample will be conducted during the next reporting period.

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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. A preliminary report will be written and sent to a committee representing the various column vendors for their review and comments.

The optimization of the operating variables in the first phase will involve generating empirical relationships which describe the parameter effects on the process response variables. This objective will be achieved by conducting an experimental program on each column using a Box-Behnken test design. The center point of the experimental design will be the suggested parameter values as reported by the column vendors. At a minimum, the response variables examined in the experimental design will include product ash and sulfur content, combustible recovery, yield, and separation efficiency.

After completion of the test program, a commercial statistical analysis program known as DESIGN-EXPERT will be used to analyze the flotation test data collected from each of the flotation column units and to produce the empirical expressions. Using these expressions, the response variables and, thus, the operating values for each flotation column will be optimized by applying an off-line optimization technique, such as the Simplex or Hooke-Jeeves methods, to the predicted results obtained from each of the empirical expressions.

In phase two, the optimized parameter values corresponding to the maximum separation efficiency value will be used to identify a point on the ultimate recovery-grade curve for each column. Exploratory tests will be conducted around this point to verify that it is an optimum. Upon verifying the optimum, the complete recovery-grade curve will be generated by conducting tests on each column over a range of feed rates while maintaining the other operating parameter values at their optimum. The same optimum conditions will be used for the treatment of an Illinois No. 6 flotation feed sample.

The recovery-grade curve generated by each column will be compared to standard release analyses test results. If the experimental recovery versus grade curve falls below the release curve, process variables such as aeration rate, frother concentration, and wash water rate will be adjusted in an effort to improve the recovery-grade relationship. Testing on a particular column will terminate when no improvement in the recovery-grade curve is realized after adjustments in the values of the critical parameters. The final recovery-product ash content and recovery-total sulfur content curves produced from each of the column technologies will be compared.

Using the empirical yield expressions, feed rates will be determined which will provide 3 different yield values for each of the flotation columns. The three yield values will be the same for each column. Tests will be conducted at the pre-determined feed rates to verify the empirical model for each column. The other operating parameters will be maintained at

their optimum values. The data from these tests will be used to compare the throughput capacities of the different flotation columns in terms of the tons per hour of clean coal produced per column cross-sectional area (tons/hr/ft²). These capacities will be correlated with air and frother consumption values.

In summary, 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, all of the column technologies to be tested in this study have been installed at the Illinois Coal Development Park in Carterville, Illinois. A total of 25 fifty-five gallon drums of Illinois No.5 coal flotation feed was collected at a local coal preparation plant, which is presently using conventional flotation. A characterization study of this sample, which will include analyses for composition, particle size, washability, and floatability, will be conducted during the next reporting period.

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.

Significance of the Proposed Work

The proposed research project will evaluate commercially available column flotation technologies that can be used immediately by the Illinois coal industry to reduce the sulfur and ash content of their coal product. The Illinois coal industry is facing potential loss of over 25% of their total coal market as a result of sulfur dioxide emission restrictions contained in the Clean Air Act Amendments of 1990 (IENR, 1992). Phase I of the Clean Air Act will begin in 1995, with more severe phase II restrictions beginning in the year 2000. There is presently a great need to better clean sulfur from Illinois coal. Only existing commercially available technology, where problems of scale-up and industrial scale application have already been solved, can produce the fast results that the Illinois coal industry must have to remain strong and competitive.

In addition, there are several coal preparation plants operating in the Illinois Coal Basin that are forced to

dispose of the combustible coal in the fine fraction due to the inability of conventional flotation cells to treat coals having a large clay content. High product ash contents and severe dewatering difficulties are typical problems encountered where there is a large amount of clays present. These waste streams represent the best liberated and most cleanable portion of the coal in a preparation plant. Due to the use of wash water, flotation columns can effectively treat fine coals containing a high clay content while maintaining high combustible recovery values.

This research project will fill a need for comparative testing not satisfied by previous research or existing industrial services. Numerous studies, including several funded by the Illinois Clean Coal Institute (ICCI), have demonstrated that specific column flotation technologies can clean sulfur and ash from Illinois coal. Commercial vendors, such as Diester, Pyramid Resources, and Control International, have laboratory facilities to conduct tests on perspective buyer's feed stocks. What is lacking is a neutral test site that enables direct "head to head" tests of competing column technologies to be conducted under equal operating conditions.

EXPERIMENTAL PROCEDURES

A total of 25 fifty-five gallon drums of flotation feed was collected at Kerr-McGee's Galatia Preparation Plant during the period of one operating day. This flotation feed sample was an Illinois No. 5 seam coal. The characterization of this sample will be conducted during the next reporting period.

RESULTS AND DISCUSSION

There are no results or discussion to report since there were no major tasks involving the collection of data scheduled to be conducted within this reporting period.

CONCLUSIONS AND RECOMMENDATIONS

At this point, there are no conclusions to be drawn. During the next reporting period, the sample characterization (Task 2) and the operating parameter optimization tests (Task 3) will begin. The project is presently on schedule according to the original project milestone chart.

REFERENCES

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- Flint, I. M., MacPhail, P., and Dobby, G. S., 1988, "Aersol Frother Addition in Column Flotation," *CIM Bulletin*, **81** (913), pp. 81 - 84.
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- 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.

DISCLAIMER

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PROJECT MANAGEMENT REPORT**September 1 through November 30, 1993****Project Title: A Comparison Study of Column Flotation
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COMMENTS

The total project costs expended during this reporting period was \$25,012 which is comparable to the projected amount of \$25,824. A substantially greater amount than that projected in the proposal was expended for materials and supplies due to unexpected costs associated with the construction and modification of the flotation columns and the ordering of lab supplies needed to initiate the experiments. Labor costs were less due to the matching funds provided by the Department of Mining Engineering for graduate research assistant support which was utilized during this reporting period.

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	400	8,352	2,000	1,514	25,012
Sept. 1, 1993 to Feb. 28, 1994	Projected	15,284	1,218	4,750	900	9,600	5,700	3,745	41,197
	Estimated								
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								
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)

Months and Quarters

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

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END