DEVELOPMENT, TESTING, AND DEMONSTRATION OF AN OPTIMAL FINE COAL CLEANING CIRCUIT

Final Technical Report

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Principal Authors:

Steven R. Hadley
R. Mike Mishra
Michael Placha

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Prepared by:

Cyprus Emerald Resources Corporation
145 Elm Drive
Waynesburg, PA 15370

and:

Praxis Engineers, Inc.
852 North Hillview Drive
Milpitas, CA 95035

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ABSTRACT

The objective of this project was to improve the efficiency of the fine coal froth flotation circuit in commercial coal preparation plants. The plant selected for this project, Cyprus Emerald Coal Preparation Plant, cleans 1200-1400 tph of Pittsburgh seam raw coal and uses conventional flotation cells to clean the minus 100-mesh size fraction. The amount of coal in this size fraction is approximately 80 tph with an average ash content of 35%.

The project was carried out in two phases. In Phase I, four advanced flotation cells, i.e., a Jameson cell, an Outokumpu HG tank cell, an open column, and a packed column cell, were subjected to bench-scale testing and demonstration. In Phase II, two of these flotation cells, the Jameson cell and the packed column, were subjected to in-plant, proof-of-concept (POC) pilot plant testing both individually and in two-stage combination in order to ascertain whether a two-stage circuit results in lower levelized production costs.

The bench-scale results indicated that the Jameson cell and packed column cell would be amenable to the single- and two-stage flotation approach. POC tests using these cells determined that single-stage coal matter recovery (CMR) of 85% was possible with a product ash content of 5.5-7%. Two-stage operation resulted in a coal recovery of 90% with a clean coal ash content of 6-7.5%. This compares favorably with the plant flotation circuit recovery of 80% at a clean coal ash of 11%.

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EXECUTIVE SUMMARY

This project was carried out with funding from the U.S. Department of Energy (Project No. DE-AC22-94PC94154) with cost sharing provided by the teaming organizations, namely, Cyprus Emerald Resources Corporation and Praxis Engineers, Inc., as well as a high degree of support from the developers of the advanced flotation technologies under evaluation. The overall objective of this research effort was to improve the efficiency of fine coal flotation in preparation plants above that of currently used conventional cells. The stated approach to achieving this objective was to produce a low-ash clean coal from the flotation circuit so that the coarse coal circuit heavy-media gravity setting could be raised and additional coarse coal could be recovered. To this end, flotation units with features which have shown promise in improving the grade/recovery relationship for fine coal were tested at the bench and pilot scales.

The project work was implemented in two phases. Phase I comprised bench-scale testing of four advanced flotation processes. The test results were analyzed from the viewpoint of the process economics which formed the basis for selecting two processes for further testing in Phase II. The Phase II work comprised design and construction of a proof-of-concept (POC) flotation pilot plant which could be operated both as a single-stage and a two-stage circuit. Pilot-scale testing and demonstration of the selected configurations was performed at the Cyprus Emerald preparation plant located in Waynesburg, Pennsylvania.

The four advanced flotation technologies selected for bench-scale testing in Phase I were:

- Jameson cell
- Outokumpu HG tank cell
- Packed column
- Open column.

In addition to testing all four cells in single-stage operation, the Jameson and Outokumpu cells were tested as candidate first-stage cells because of their propensity for rapid attachment of coal particles with air bubbles and low capital and operating costs. The column cells were selected as candidate second-stage cells because of their high-efficiency separation of low-ash products from high-ash feed coals.

Samples of minus 150µ (100-mesh) raw coal flotation feed and existing flotation circuit tailings (operated to produce tailings which simulated a second-stage feed coal) were collected at the Cyprus Emerald Plant. The raw coal samples were used to evaluate the performance of the selected cells in single-stage operation or as the first stage of a two-stage operation. The tailings sample was used to evaluate the performance of the cells in second-stage applications only. Three of the four cells were tested at vendor-recommended laboratory facilities. The Outokumpu cell, was tested in the Cyprus plant because its high capacity made shipment of sufficient quantities of sample prohibitively expensive.

Table 1 describes the equipment used for the bench-scale work.

Table 1. Summary of Bench-Scale Test Equipment

Flotation Unit	Effective Cross-Sectional Area, cm^2	Height, cm	Maximum Flow Rate Tested, l/min
Jameson Cell	182.3	122.0	14.7
Jameson Cell	81.0	122.0	22.6
Outokumpu	716	59.0	94.5
Packed Column	45.6	366.0	8.2
Open Column	31.7	549.0	8.6

The vendors were given samples of the plant frother and the results of conventional bench-scale flotation tests to assist them in determining appropriate test conditions. Based on a preliminary evaluation of the plant economics, vendors were asked to target a clean coal product containing less than 5% ash at an energy recovery of approximately 85% for the feed coal sample.

Flotation Performance for the Feed Sample

Between 20 and 40 tests were conducted for each cell. In general, the performance of each flotation machine was very good with respect to both grade and recovery. Three of the four cells exceeded the goal of a 5% ash product at 85% energy recovery. Total sulfur rejections noted during the project ranged from 25 to 40%. This would equate to pyritic sulfur rejections of 40-65%. Table 2 provides performance data from selected tests using a raw coal feed sample and shows the ability of all cells to work over a wide range of quality and energy recovery. The results of all other tests are given in Section 5 of this report.

In general, a number of process variables were found to be correlated to product ash.

- Addition of wash water was found to be beneficial for each of the cells tested, although it was not as significant as expected.
- Froth depth was observed to be significant with respect to product grade and recovery. Increased froth depth resulted in improved grade (i.e., lower product ash) but reduced recovery. However, the vendors noted that, in general, this coal could be processed with relatively shallow froth depths and still achieve an excellent grade of 4% product ash.
- Increased air flow rates led to slightly higher product ash contents and recoveries for the column cells.

Table 2. Highlights of Bench-Scale Test Results (Raw Coal Sample)

	Jameson Cell		**Outokumpu**		**Packed Column**		**Open Column**	
Feed Velocity, cm/s	4.57	1.10	1.80	2.20	3.00	3.00	0.95	0.79
Aeration Rate, cm/s	NA	NA	2.4	2.4	4.2	4.2	2.4	1.6
Wash Water Velocity, cm/s	0.78	0.17	0.28	0.26	0.28	0.28	0.20	0.20
Froth Mass Loading, gm/min/cm^2	4.50	1.25	1.62	2.17	4.01	3.65	1.53	0.89
Product Ash, %	3.80	4.70	7.30	7.90	4.90	3.50	5.30	4.10
Product Sulfur, %	N/A	1.02	1.20	1.17	1.04	1.01	1.00	N/A
Energy Recovery, CMR, %	72.9	85.4	68.5	66.0	87.2	80.5	93.0	86.0

Energy recovery was found to be to be primarily a function of reagent dosage and aeration rates. Frother was the most significant reagent for the Jameson and open column cells, with increasing frother addition leading to higher recoveries. The ratio of fuel oil to frother was fixed for the packed column tests, and increasing the rate of addition was found to increase recovery.

Cell capacity was generally dictated by froth mass loading considerations for the raw coal feed, especially for the Outokumpu and open column cells. High feed mass loadings resulted in reduced recoveries or placed limits on the capacity of the cell. The froth mass loading for the Jameson and packed column cells exceeded the levels observed for the open column. In the case of the Jameson cell, the ratio of feed pipe diameter (downcomer) to froth tank area was increased during the final set of tests to evaluate the first-stage capacity (high-capacity tests). These tests achieved a froth loading of 2.7 tph/m^2 (4.5 gm/min/cm$^{2)}$ with a recovery of 73%. This result indicates that the Jameson cell could be used at much higher capacities in a first-stage application than as a single-stage unit.

Flotation Performance for the Tailings Sample

Ten tests were run to evaluate the cleaning of the tailings using open and packed column cells as second-stage units. Typical results, shown in Table 3, indicate that a relatively low-ash product can be recovered from a feed containing 40-50% ash. This is equivalent to a combined first- and second-stage energy recovery of 93-96%. The column cells achieved good separation efficiency at feed velocities in the range of 1.8-3 cm/sec. The maximum froth loading measured in the second-stage test work was 0.9 tph/m^2 (1.53 gm/min/cm^2). This constraint is within the anticipated requirements for processing dilute feed slurries expected for second-stage operations. The expected residence time requirement for second-stage column cell operation is 2-4 minutes.

Table 3. Highlights of Bench-Scale Test Results (Tailings Sample)

	Packed Column	Open Column
Test Number	T3	27
Feed Velocity, cm/s	2.97	1.84
Aeration Rate, cm/s	4.2	2.5
Wash Water Velocity, cm/s	0.28	0.20
Froth Mass Loading, gm/min/cm^2	1.06	1.53
Product Ash, %	6.5	8.1
Energy Recovery, CMR, %	73.9	88.0

Process Economics

Process economics were analyzed using two distinct approaches. In both cases, levelized costs were used as the basis of comparison. The first approach consists of viewing the fine coal circuit by itself. In this approach, four single-stage and four two-stage flotation circuits are compared on the basis of their levelized costs, which include capital costs, operating costs, and the amount of energy recovered from an equal amount of feed. These data are summarized in Table 4, which also shows the same parameters for the conventional flotation cells. In addition, the ash content of the various products is shown for purposes of comparison.

Table 4. Economic Comparison of Flotation Circuits

Circuit	Levelized Cost, $/MMBtu	Energy Recovery, %	Product Ash (db)
Conventional Flotation	0.20	85.0	7.5
Jameson Cell	0.21	90.1	4.2
Outokumpu	0.20	85.0	8.0
Open Column	0.16	93.0	5.3
Packed Column	0.18	91.4	4.9
Jameson/Packed Column	0.16	92.9	4.4
Jameson/Open Column	0.14	96.8	4.9
Outokumpu/Packed Column	0.16	91.8	7.1
Outokumpu/Open Column	0.14	96.3	7.5

If only a single-stage circuit were to be designed and built, the open column has an advantage when both the product quality and levelized costs are considered. However, two-stage circuits are generally more cost-effective than single-stage circuits. Their levelized costs are similar in all four cases, and as long as the fine coal circuit is considered in isolation, any of these four alternatives would perform equally well.

In the second approach, the flotation circuit is analyzed as a component in the whole cleaning plant. In this approach, the effects of yield and quality in the fines circuit are studied interactively with the coarse coal cleaning circuits, e.g., heavy-media cyclones, in the plant. In this view, a two-stage circuit using a Jameson cell with an open or a packed column makes products with a significantly lower ash content while still achieving high energy recoveries. This improvement in the quality of the fines would allow the plant operators to increase the separation gravity in the coarse circuits, resulting in a slight increase in ash and yield for their products, while still maintaining the same overall product quality (Btu, ash, moisture, etc.) on a plant-wide basis. An economic analysis carried out for a target plant product with a heating value of 13,000 Btu/lb (as-received basis) showed that an overall 0.8% gain in the plant recovery can be achieved when using the Jameson/packed column two-stage option. When this increased energy recovery is factored into the levelized costs for this circuit, it results in the lowest overall product cost of $0.125/MMBtu.

Equipment Selection for Phase II POC Pilot-Scale Tests

After reviewing the performance data and related economics, the flotation machines and circuits recommended for POC testing at the pilot scale were:

- Single-stage Jameson cell
- Single-stage packed column operation
- First-stage Jameson cell, second-stage packed column.

The Jameson cell was selected for the first stage based on its good performance and low operating costs. The high-capacity tests indicated that it has a good potential for recovering a low-ash product with a high froth mass loading. Both the open and packed column cells achieved good process separations and demonstrated the potential for high-capacity operations with dilute feed slurries (second-stage feed conditions), and either cell would be suitable for demonstration of two-stage circuits. Both cells were capable of producing a product containing less than 4% ash from the raw coal. The packed column was selected in favor of the open column because of its:

- Potential for achieving high froth mass loading levels
- Process control capability via regulation of froth depth
- Enhanced process separation efficiency when producing a low-ash product.

POC Design and Construction

A flexible POC pilot plant was constructed in which the Jameson and packed column cells could each be operated as a single-stage circuit or as a two-stage combined circuit with recleaning of the Jameson cell first-stage rejects in the packed column. The Jameson cell was retrofitted with adjustable cell walls in order to alter the cell cross-sectional area, and therefore the froth mass loading, independently of the feed rate. The packed column was 30.4 cm in diameter and 7.5 meter tall, with a feed point 3.0 meters from the top and packing openings of 1.3 cm and 1.9 cm. In an effort to lower reagent usage in the packed column, portions of the wash water were injected into the packing at varying depths from the top of the cell. This technique helped to thicken the froth by creating a drainage zone before the cell discharge, instead of relying on the thickening effect of higher fuel oil dosages.

POC Operating Conditions

The POC test work was conducted in the Cyprus preparation plant over a period of eight months. The goals of the POC tests were to verify the separation efficiency achieved in the bench-scale tests at similar froth loading capacities and to reduce reagent consumption in order to lower operating costs. A three-phase test program was adopted to implement these objectives, consisting of:

- Single-stage tests for the Jameson and packed column cells
- Two-stage tests where the Jameson tailings are recleaned in the packed column cell
- Extensive demonstration testing of the two devices using two-stage operation.

The range of test parameters used in POC operations is listed in Table 5 for each circuit. In the case of the first-stage Jameson cell tests, the primary objective was to achieve a low product ash at high capacity since any coal lost to the tailings would be recovered in the second-stage column cells in any case. Flow rates up to the maximum level tested at the bench scale were used and other cell parameters were varied accordingly (see Table 5). All reagents used in the two-stage circuit tests were added to the Jameson cell feed slurry. Based on the results of the initial test work, wash water was split between froth bed injection and a perforated tray mounted above the froth. Approximately 20-30% of the water was added to the tray. This modification prevented froth stagnation at low frother concentrations and was used for all subsequent tests including all of the single-stage tests.

Table 5. Range of Test Parameters During POC Operations

Test Parameter	Single-Stage Jameson Cell	Single-Stage Packed Column	First-Stage Jameson Cell	Second-Stage Packed Column
Feed Flow Rate, cm/s	4.5/2.6*	3.7/5.2	2.6/3.8/4.5	3.7/5.4/6.4
Fuel Oil, kg/t	0.17-0.37	0.15-0.95	0.11-0.76	-
Frother, kg/t	0.19-0.50	0.17-0.76	0.15-0.76	-
Frother, ppm	7-14	7-21	4.8-16.5	
Froth Depth, cm	38-46	165-368	25-46	264-419
Air Flow, cm/s	1.7-2.3	2.6-8.2	1.3-2.2	1.3-5.3
Wash Water, cm/s	0.34-0.47	0.26-0.52	0.25-0.5	0.16-0.6

*Froth tank feed rate = 4.5, Raw coal feed rate = 2.6.

The second-stage packed column conditions were chosen to achieve high recoveries and a sufficiently low product ash level as to result in a low combined two-stage product ash. The range in air flow was reduced and the range of froth depth increased to improve separation efficiency when processing the high-ash Jameson cell rejects. As with the single-stage operation, various wash water injections were tested.

POC Test Results

Jameson Cell Single-Stage Tests: After preliminary operations, it was noted that cell performance improved when the feed solids were more dilute. Following discussions with Jameson cell representatives, 40% of the Jameson cell refuse stream was recycled back to the feed to dilute the feed solids content and provide another opportunity to capture the lost coal in the recycle stream. Tests were run with a total feed rate of 260 l/min, consisting of a new coal slurry feed rate of 160 l/min and 100 l/min tailings recycle. Average conditions for the other process parameters were an air flow rate of 2.0 cm/s, wash water rate of 0.45 cm/s (25% to the wash water tray), and a froth depth of 38 cm. At a frother dosage of 0.4 kg/t, the coal matter recovery (CMR) using 40% recycle was approximately 85% at a product ash content of 6.0%. These data compare favorably with earlier tests (80% CMR at 5.5% product ash) in which no tailings recycling was used.

Packed Column Single-Stage Tests: The packed column test work emphasized reducing reagent usage while still achieving good separations. Reagent dosage levels used in the bench-scale test work were the starting point for the POC tests. It was found that by proper adjustment of froth level, air flow rate, and method of wash water addition, relatively low reagent dosages could be used. Frother and fuel oil dosages as low as 0.2-0.4 kg/t and 0.3-0.4 kg/t, respectively, achieved CMR values on the order of 85% (equivalent to performance of 0.8 kg/t frother, 1 kg/t fuel oil tests) by simultaneously increasing the froth depth (270 cm to 350 cm) and reducing the air flow rate (7 cm/s to 5 cm/s). This relationship is attributed to the effect of oil on the structure and viscosity of the froth.

Increasing the froth depth above 356 cm produced a noticeable drop in recovery, and attempts to raise recovery produced a fast flowing froth which has been related to poor clean coal ash quality.

The importance of froth drainage when using lower fuel oil dosages was also noted. The incorporation of a drainage zone at the top of the cell led to a reduction in clean coal ash content at the same recovery of 85%. The drainage zone enabled operation of the cell at a lower froth depth and slightly less air flow.

Packed Column Cell Second-Stage Operation: The tailings from the Jameson cell were recleaned in the packed column. In this case also, cell operation was determined to be sensitive to the same process variables as in single-stage operation. High fuel oil dosages required high air flows to get combined circuit recoveries above 80%. Reducing the fuel oil and frother with lower air flow was found to still achieve good recovery. The following conditions were used for the second-stage and resulted in good performance:

- Frother dosage: < 0.6 kg/t
- Fuel oil dosage: < 0.8 kg/t
- Froth separation depth: > 200 cm
- Froth drainage depth: < 130 cm

The froth ash content was found to be correlated to the second-stage feed ash content. It is important to note that the latter is itself related to the initial frother dosage which was found to be the major process variable affecting first-stage performance.

Comparison of the test data by feed flow rate indicates that cell performance is only marginally reduced by changes in the flow rate (see Table 6). The average test conditions also illustrate how the test work progressed towards lower reagent dosages, especially fuel oil. The high flow rate tests required a reduction in fuel oil dosage for proper downcomer operation, as previously stated.

Table 6. Packed Column Second-Stage Performance: Low and High Flow Rate Averages

Average Test Parameter	**160 l/min Feed Rate (3.7 cm/s)**	**275 l/min Feed Rate (6.3 cm/s)**
Feed Ash, %	70.0	67.2
Fuel Oil, kg/t	0.39	0.32
Frother, kg/t	0.28	0.33
Air Flow, cm/s	3.4	2.3
Wash Water, cm/s	0.26	0.4
Froth Depth, cm	370	358
CC Ash, %	12.6	11.4
Refuse Ash, %	85.8	82.3
CMR, %	61.1	56.6

The trends of the second-stage test results are summarized with respect to feed ash in Table 7 to better clarify flow rate comparisons. Second-stage recovery is shown to drop with increasing feed ash for all flow rates. The results indicate that lower flow rates result in slightly higher second-stage recovery (63.5% vs. 56.5%).

Table 7. Packed Column Second-Stage Performance: Trend Line Data Summary

Feed Ash, %	Clean Coal Ash, %	Refuse Ash, %	Second-Stage CMR, %
Feed Rate: 3.7 & 4.9 cm/s			
60	6	80	63.5
65	9	81	57.8
70	12	82	50.3
Feed Rate: 6 cm/s			
60	7	77	56.5
65	11	80	55.3
70	n/a	n/a	
Feed Rate: 6 cm/s, deep wash water injection			
65	20	80	57.1

Feed solids >1% solids
Initial frother concentration <0.6 kg/t or <15 ppm

Table 7 also illustrates the effect of adding wash water too deep into the froth zone. When most of the wash water was injected at a depth of 135 cm, it resulted in a significant increase in product ash in the range of 15-28% in spite of the froth thickening achieved by the large froth drainage zone. This was attributed to an insufficient froth washing zone (distance between water injection point and froth/slurry interface).

<u>Combined Two-Stage Performance</u>: Efficient operation of the two-stage circuit required compatibility between each stage with respect to selection of operating conditions. The primary parameter that required optimization was fuel oil dosage. Higher levels of fuel oil were favorable for packed column operation in that lower froth bed depths could be used and a consistent low ash product produced, although higher air flows would be required. However, high levels of fuel oil were detrimental to Jameson cell downcomer performance at high flow rates. Test work indicated that if the fuel oil dosage was kept in the range of 0.2 to 0.4 kg/t, high recoveries from the first stage would be realized and good two-stage performance could be achieved.

The conditions for optimal results are given below:

• Fuel oil dosage:	0.2 to 0.4 kg/t
• Frother dosage:	0.2 to 0.6 kg/t
• Jameson cell froth depth:	>25 cm
• Packed column separation froth depth:	> 200 cm
• Packed column cell drainage froth depth:	< 130 cm
• Packed column air flow:	< 4 cm/s

The two-stage circuit consistently achieved recoveries above 80%, with an average of 89% for these conditions. The average recovery from the first stage was 74% and the average second-stage recovery was 56%. The results were found to correlate best with feed ash for both low (160 l/min or 2.6 cm/s) and high (275 l/min or 4.5 cm/s) feed rates. In general, the feed ash during the low flow rate tests was higher than during the subsequent high flow rate tests. The feed rate ash had little impact on the overall recovery of the system, but did cause a slight increase in the product ash content. The data trend indicates that with a feed ash below 30% the clean coal ash would be 5.5%, increasing to 7% for a feed ash of approximately 45%.

Two Stage Demonstration Tests

The key emphasis of the demonstration tests was on evaluating long-term two-stage circuit operations. These tests represent pilot plant operation lasting 17 shifts. The major process variables tested were frother and fuel oil dosage, with only minor adjustments to equipment parameter settings as determined in the previous development work. Combined two-stage coal recovery ranged from 70% at 0.15 kg/t frother to 90% at 0.3 kg/t frother. Recovery ranged from approximately 50 to 75% for the first-stage Jameson cell and 40-60% for the second-stage packed column cell, which is approximately 2-5% below recoveries measured previously. In addition, the clean coal ash content was higher for both the Jameson cell and packed column cell. For instance, Jameson cell product ash ranged from 6 to 8% compared with 5-6.5% ash measured previously for similar test conditions. The packed column second-stage clean coal ash increased from 10 to 13% ash at a feed ash of 65%. These differences were attributed to a change in feed coal flotation properties during the demonstration tests as indicated by a large drop in recovery from the conventional plant flotation circuit (80% to 43%).

The second-stage performance results are more consistent when test results are trended with respect to feed ash. At a second-stage feed ash of 65%, the clean coal ash content ranged from 11 to 15%, with a refuse ash of approximately 80%. At a second-stage feed ash of 55% the clean coal ash was approximately 8-11%.

In general, the demonstration tests confirm that good flotation performance can be achieved using the two-stage circuit approach. Stable operations were achieved during pilot plant operations lasting 17 shifts, especially when compared with the plant flotation circuit operation. The two-stage circuit recovery was consistently higher than 80% for frother dosages greater than 0.2 kg/t. These results are in agreement with the bench-scale test results with respect to capacity and efficiency and substantiate the economic analysis.

1.0 INTRODUCTION

The overall goal of this project was to produce a low-ash clean coal from the flotation circuit so that the coarse coal circuit heavy-media gravity setting could be raised to recover additional clean coal from the coarse coal circuit. To this end, four advanced flotation units with features which have shown promise in improving the grade/recovery relationship for fine coal were tested at the bench and pilot scales.

The work activities of this project were structured in two phases:

- Phase I: Bench-scale testing and equipment selection
- Phase II: In-plant, proof-of-concept (POC), pilot-scale testing.

In Phase I, bench-scale tests of four leading advanced flotation cells were conducted in order to recommend single- and two-stage circuits for testing at the POC scale in Phase II. The cells that were tested were:

- Jameson cell
- Outokumpu HG tank cell
- Packed column
- Open column.

In Phase II, proof-of-concept (POC) scale tests using the Jameson cell and the packed column were conducted at the coal preparation plant in single- and two-stage combinations in order to ascertain whether a two-stage circuit results in lower levelized production costs.

The main project objectives can be summarized as follows:

- Test single- and two-stage circuit configurations at the pilot plant level
- Quantify the clean coal ash and recovery relationship for each circuit
- Estimate operating costs, especially reagent requirements, as a function of recovery and establish operating conditions that minimize these costs without sacrificing recovery.

This is the final report for the project. The report is structured in sections corresponding to each major work activity. In general, Sections 3-9 cover the Phase I work and Sections 10-13 cover the Phase II demonstration tests at the coal preparation plant. An outline of the material covered in each section is given below.

Section 2 outlines the project objectives and the criteria used for the selection of the advanced flotation equipment for bench scale evaluation under this project.

Section 3 describes test sample collection and related sample analysis.

In Section 4, plant data and initial construction of a two-stage material balance are discussed.

In Section 5, the bench-scale test work is described and the results are analyzed. In general, the testing included the following:

- Each cell was tested for single-stage operation.
- The Jameson and Outokumpu cells were also tested for use as the first stage of a two-stage circuit.
- The open and packed column cells were tested for use as the second stage of a two-stage circuit.

In Section 6, a conceptual design based on the bench-scale test results is developed for both single- and two-stage circuits. The bench-scale test results are scaled up and circuit material balances are completed for the following eight configurations:

Single-Stage Operation	**Two-Stage Operation**
Jameson Cell	Jameson/Open Column
Outokumpu HG Tank Cell	Jameson/Packed Column
Open Column	Outokumpu/Open Column
Packed Column	Outokumpu/Packed Column

Section 7 presents the economics of using each single- and two-stage circuit at the coal preparation plant. Levelized product costs are used as the basis for making comparisons between circuits. The economics include a sensitivity analysis of coal and process assumptions that impact the levelized costs.

Section 8 presents a discussion of the merits of two-stage circuits.

Section 9 presents equipment selection recommendations for the in-plant POC pilot-scale tests.

Section 10 describes design and construction of the POC plant.

Section 11 provides a detailed description of POC operations. It includes a discussion of initial equipment problems and solutions. Parametric test results for single- and two-stage operations including a novel tailings recycle mode of operation for the single-stage Jameson cell are discussed.

Section 12 describes the POC demonstration tests. These tests were carried out in two phases and represent a total of 80 hours of pilot plant operations.

Section 13 summarizes the conclusions of project test work and provides recommendations for circuit design and optimal conditions for circuit operation.

2.0 PROJECT OBJECTIVES

The objective of the project is to test advanced flotation concepts in order to improve fine coal cleaning and develop an optimal circuit configuration. This project objective may be broken down into the following subsections:

- Evaluate emerging flotation equipment and practices and select four advanced flotation cells.
- Conduct bench-scale studies to establish the relationships between capacity and product recovery and ash content for each cell.
- Conduct economic analyses of the bench-scale results and select two of the most promising advanced flotation cells for POC testing.
- Design and construct a pilot-scale POC flotation circuit to conduct single- and two-stage flotation tests.
- Test and demonstrate single- and two-stage circuits to gather operating data for accurate estimation of full-scale plant operations.

The criteria for selection of advanced flotation equipment are summarized below.

- Good cleaning performance, i.e., ash and sulfur rejection, at high Btu recovery levels
- Sufficient data available at the laboratory scale, or larger, to substantiate process performance claims
- Demonstrated operations for coal or other mineral applications
- Ability to recover a high-grade coal product from a raw coal feed with high specific capacity. (This is important for rate-limited cells when used as first-stage units.)
- Efficient recovery of low-ash coal from a high-ash feed coal. (This is important for second-stage cells receiving a high-ash feed.)
- Amenability to process control under varying plant conditions.

The four flotation cells selected for bench-scale test work were:

- A Jameson cell
- An Outokumpu Mintec HG tank cell
- A Pyramid Resources, Inc. open column cell
- A packed column cell from Mineral Technologies International, Inc. (MTI).

Four equipment vendors with proven expertise in conducting bench-scale test work were selected for the work. The Jameson cell was tested at Southern Illinois University at Carbondale (SIUC), Carbondale, IL; the open column tests were conducted at the Pyramid Resources, Inc. facility in Salt Lake City, UT; the packed column tests were conducted at MTI facilities in Morgantown, WV; and the Outokumpu Mintec HG tank cell was tested at the coal preparation plant.

3.0 SAMPLE COLLECTION AND ANALYSIS

3.1 Sample Collection

Representative samples of the 150µ x 0 (100M x 0) stream from the Emerald plant were collected to conduct the bench-scale test work. Multiple samples were collected to correspond to each flotation circuit to be tested. These were:

- Minus 100-mesh raw coal (classifying cyclone overflow) flotation feed
- Flotation tailings
- Froth flotation product from the existing flotation cells.

Relatively large quantities of the first two streams, i.e., feed and tailings, were collected in order to ship them to vendors for bench-scale testing. In addition, 5-gallon samples from all three streams were collected and set aside for analytical purposes.

A total of 45 drums in five sets (9 drums/set) of flotation feed and 10 drums in another five sets (2 drums/set) of the flotation tailings were collected.

The drums were filled using a flexible hose connected to the sampling port of the plant feed and tailings streams. During sample collection, the hose was transferred from one drum to another while attempting to minimize spillage. The samples were collected in increments of 5 gallons each. Sample collection lasted over five shifts.

3.2 Sample Analysis

The 5-gallon analytical samples collected over the entire sampling period were combined to form raw coal and tailings composite samples which were used for the preliminary analytical and characterization work. Coal characterization tests were conducted on plant flotation feed, product, and tailings samples to provide information necessary for bench-scale testing. The 150µ x 0 (100M x 0) plant flotation feed coal and the tailings sample were fully characterized for proximate analysis as per ASTM standards (ASTM D 3173, D 3174, D 3175); total sulfur and forms of sulfur were determined based on ASTM D 2492. The plant feed coal analysis and plant flotation tailing analyses are presented in Table 8.

Table 8. Plant Flotation Feed Coal and Flotation Tailings Analyses

Parameter	Flotation Feed	Flotation Tailings
Ash, %	19.99	47.83
Sulfur forms, %		
Sulfatic sulfur	0.00	0.01
Pyritic sulfur	0.49	1.41
Organic sulfur	0.61	0.33
Total sulfur, %	1.10	1.75
Btu/lb	11,911	7,359

The particle size distribution of the plant feed was determined using a Microtrac Analyzer. The feed was 95% passing 150 microns and 50% passing 40 microns.

Washability tests were also conducted on the plant feed coal based on ASTM D 4371 using the centrifuge sink/float technique, the results of which are presented in Table 9.

Table 9. Plant Flotation Feed Coal Washability Analysis (100M x 0)

Specific Gravity Fraction		Elementary Data					Cumulative Computed Data					Analysis		
		Wt %	Ash	Sulfur	Btu*	SO2/ MBtu	Wt %	Ash	Sulfur	Btu	SO2/ MBtu	Btu Recovery	CMR %	Ash Rejection %
Float	1.3	25.4	2.2	0.90	14768	1.22	25.4	2.2	0.9	14768	1.22	30.7	30.3	96.9
1.3	1.4	34.4	5.6	0.99	14142	1.40	59.7	4.2	0.95	14408	1.32	70.6	69.9	86.2
1.4	1.5	14.6	10.4	0.95	13270	1.43	74.3	5.4	0.95	14184	1.34	86.5	85.9	77.8
1.5	1.6	6.2	11.8	0.82	13017	1.26	80.5	5.9	0.94	14095	1.34	93.1	92.5	73.8
1.6	1.8	3.3	21.1	0.87	11381	1.53	83.7	6.5	0.94	13990	1.34	96.1	95.6	70.0
1.8	Sink	16.3	78.0	2.09	2886	14.48	100.0	18.1	1.13	12184	1.85	100.0	100.0	0.0

* Estimated

These washability data provide a good estimate of the expected flotation circuit performance and indicate that at energy recoveries of 85% a product ash content of about 5.3% would be achieved while about 35% of the total sulfur would be rejected. Since most of the rejected sulfur is pyritic in nature, pyritic sulfur rejections may reach about 70%.

3.3 Batch Flotation Tests

The batch feed and tailings samples were tested in a conventional (batch) flotation cell to determine a benchmark laboratory performance against which the performance of all the advanced flotation machines would be assessed. The froth product from a single-stage batch experiment was repulped and floated in a second stage. Second-stage froth recleaning was incorporated in an effort to simulate froth washing techniques used in advanced flotation equipment. The product of this two-stage bench flotation procedure was intended to represent the product expected from the advanced flotation cells. The results of the batch flotation testing of the raw coal and tailings samples are presented in Table 10 and Table 11.

The results for the two-stage flotation test on the feed coal show that advanced cells should be able to provide energy recoveries of 85-90% at 5% product ash values, while rejecting 30% of the total sulfur.

Table 10. Batch Flotation Tests on Plant Flotation Feed

One Stage Flotation Using 5.2% Solids
Collector (Fuel oil) 0.40 kg/tonne coal (.81 lb/ton)
Frother (SM222) 0.17 kg/tonne coal (0.35 lb/ton)

		Product(Direct Values)			Product(Cumulative Values)			Performance	
Stage	Flotation Time	Wt %	Ash %	Sulfur %	Yield %	Ash %	Sulfur %	Btu Rec%	Ash Rej %
Rougher	30 sec	42	6.6	1.09	42.0	6.6	1.09	49.2	86
	60 sec	9.9	6.7	1.09	51.9	6.6	1.09	60.8	83
	120 sec	7.4	9.2	1.12	59.3	7.0	1.09	69.2	80
	Tails	40.7	39.9	1.13					
Total					100.0	20.4	1.11		

One Stage Flotation Using 5.2% Solids
Collector (Fuel oil) 0.56 kg/tonne coal (1.11 lb/ton)
Frother (SM222) 0.23 kg/tonne coal (0.47 lb/ton)

		Product(Direct Values)			Product(Cumulative Values)			Performance	
Stage	Flotation Time	Wt %	Ash %	Sulfur %	Yield %	Ash %	Sulfur %	Btu Rec%	Ash Rej %
Rougher	30 sec	51.0	6.6	1.10	51.0	6.6	1.10	60.7	84
	60 sec	13.3	7.4	1.14	64.2	6.7	1.11	76.3	80
	120 sec	9.9	9.4	1.22	74.2	7.1	1.12	87.8	76
	Tails	25.8	62.9	1.01					
Total					100.0%	21.5%	1.09%		

Two Stage Flotation Using 2.9% Solids
Collector (Fuel oil) 0.99 kg/tonne (1.98 lb/ton) & 1.13 kg/tonne (2.25 lb/ton) -1st and 2nd stage resp.
Frother (SM222) 0.42 kg/tonne (0.84 lb/ton) & 0.48 kg/tonne (0.96 lb/ton) -1st and 2nd stage resp.

		Product(Direct Values)			Product(Cumulative Values)			Performance	
Stage	Flotation Time	Wt %	Ash %	Sulfur %	Yield %	Ash %	Sulfur %	Btu Rec%	Ash Rej %
Cleaner	30 sec	64.7	4.0	1.09	64.7	4.0	1.09	76.1	85.9
	60 sec	7.1	6.6	1.22	71.8	4.3	1.10	84.2	83.4
	120 sec	5.9	6.3	1.22	77.7	4.4	1.11	91.0	81.4
Cleaner	Tails	2.4	61.3	1.77	80.0	6.1	1.13	92.1	73.5
Rougher	Tails	20.0	67.8	1.21					
Total					100.0	18.4	1.15		

Table 11. Batch Flotation Tests on Plant Flotation Tailings

One Stage Flotation
Collector (Fuel oil) 1.9 kg/tonne (3.8 lb/ton)
Frother (SM222) 0.7 kg/tonne (01.4 lb/ton)

		Product(Direct Values)			Product(Cumulative Values)			Performance	
Stage	Flotation Time	Wt %	Ash %	Sulfur %	Yield %	Ash %	Sulfur %	Btu Rec%	Ash Rej %
Rougher	30 sec	22.5	15.17	1.75	15.2	22.5	1.8	30.2	90.7
	60 sec	10.0	9.87	1.66	13.5	32.5	1.7	44.4	88.0
	120 sec	7.5	14.05	1.12	13.6	40.0	1.6	54.6	85.2
	Tails	60.0	52.14	2.09					
Total					100.0	36.7	1.68		

Two Stage Flotation
Collector (Fuel oil) 0.9 kg/tonne (1.8 lb/ton) in 2nd stage resp.
Frother (SM222) 0.4 kg/tonne (0.8 lb/ton) in both 1st and 2nd stage resp.

		Product(Direct Values)			Product(Cumulative Values)			Performance	
Stage	Flotation Time	Wt %	Ash %	Sulfur %	Yield %	Ash %	Sulfur %	Btu Rec%	Ash Rej %
Cleaner	30 sec	16.1	5.64	1.57	16.1	5.6	1.57	24.0	97.5
	60 sec	8.8	6.05	1.59	24.8	5.8	1.58	37.1	96.1
Cleaner	Tails	13.3	24.10	2.31	38.1	12.2	1.83	53.0	87.4
Rougher	Tails, +48 mesh	16.3	8.32	1.93					
Rougher	Tails, -48 mesh	45.6	67.79	2.11					
Total					100.0	36.9	1.82		

3.4 QA/QC Analysis

Verification of vendor analyses for ash and total sulfur was completed in two steps: (I) repeat analysis of project feed coal samples during testing and (ii) analysis of selected bench-scale samples by an independent laboratory. First, subsamples of the project samples sent to the vendors were analyzed at the coal preparation plant laboratory. The vendors were also requested to analyze the feed samples periodically during their test work. The analysis of the plant flotation feed and tailings samples collected for the bench-scale test work is presented in Table 12. The corresponding vendor analysis is presented in Table 13 and Table 14.

As discussed in Section 5, a bench-scale Outokumpu HG tank cell was installed and tested at the preparation plant site using a slipstream of the plant flotation feed. Therefore, for this cell, comparison of the plant flotation feed analysis with the project sample analysis does not represent a check on analytical procedures. For this reason, the Outokumpu analysis is not presented in Table 14.

Table 12. Analysis of Plant Flotation Feed and Tailings Samples

Set ID	Sample	Ash, %	Sulfur, %	Solids, Wt %
A	Raw Coal	20.0	1.09	5.21
B	Raw Coal	19.0	1.07	5.20
C+D	Raw Coal	18.3	1.11	2.80
E	Raw Coal	18.1	1.11	2.75
	Tailings	47.8	1.75	N/A

Table 13. Vendor Analysis of Feed Coal (Flotation Feed) to Test Cells

Vendor (Test Site)	Ash, %	Sulfur, %
Jameson Cell (SIUC)		
Raw Coal A	20.2	1.00
	20.4	
Raw Coal B	19.5	
	21.5	
	20.0	
Packed Column (MTI)		
Raw Coal A	20.6	1.12
	20.2	1.12
	21.0	1.10
	20.6	1.10
Raw Coal B	20.0	1.12
	19.0	1.13
	19.6	1.10
Open Column (Pyramid)		
Raw Coal B	20.2	.87
	20.6	1.26
Raw Coals B&C	20.5	1.40
	19.6	1.60
Raw Coal D	19.5	1.46
	19.7	0.87
	19.1	0.92
Raw Coal E	19.1	
	19.9	
	18.5	
	18.6	

Table 14. Vendor Analysis of Feed Coal (Tailings) to Test Cells

Vendor (Test Site)	Ash, %	Sulfur, %
Packed Column (MTI)	46.1	2.10
Open Column (Pyramid)	46.6	1.30
	42.3	
	48.6	
	45.7	
	44.5	

The second step in checking the vendor analyses was to request that splits of the test samples be sent to an independent laboratory for analysis. A comparison of the independent laboratory analyses with the corresponding vendor results is shown in Table 15.

Table 15. Comparison of Vendor and Independent Laboratory Analyses

Sample	Vendor		Independent Laboratory	
	Ash, %	Sulfur, %	Ash, %	Sulfur, %
Jameson Cell	20.7	N/A	20.7	1.00
	4.2	N/A	4.5	0.97
	55.9	N/A	50.2	1.10
	20.4	N/A	20.2	1.07
	3.8	N/A	4.2	0.92
	46.5	N/A	45.8	1.20
	21.5	N/A	21.7	1.01
	4.5	N/A	5.1	0.96
	56.0	N/A	55.5	1.12
Packed Column				
B-4 feed	20.0	1.12	19.3	1.11
	4.9	1.07	4.6	1.05
	70.4	1.37	71.2	1.25
B-16 feed	20.0	1.12	18.5	1.12
	4.9	1.04	4.7	1.03
	59.8	1.38	60.8	1.34
B-17	3.5	1.01	3.4	0.99
	51.4	1.40	52.7	1.34
C-1	19.7	N/A	19.9	1.15
	4.8	N/A	4.6	1.01
	50.6	N/A	51.0	1.27

The vendor analytical techniques are within ASTM specifications for ash and sulfur with the exception of the Pyramid open column analysis for sulfur, shown in Table 13. After a review of these results, Pyramid was requested to use an outside laboratory for this sulfur analysis. Sulfur measurements for the Jameson cell were also completed by an outside laboratory. No other significant differences in the analyses between laboratories were detected.

4.0 PLANT DATA AND FLOTATION CIRCUIT MATERIAL BALANCE ESTIMATES

4.1 Conventional Flotation

Before the start of the test program, historical plant flotation data were reviewed to assess circuit performance. Sample sets of the flotation circuit feed, clean coal, and tailings were compiled as shown in Table 16.

Table 16. Historical Plant Flotation Performance

Ash, %			Sulfur, %			Energy	Total Sulfur
Feed	**Product**	**Tailings**	**Feed**	**Product**	**Tailings**	**Recovery**	**Rejection, %**
28.6	7.8	63.5	1.64	1.81	2.13	81.0	30.8
26.7	8.4	76.1	1.62	1.65	2.09	91.1	25.8
28.4	7.4	61.9	1.62	1.63	2.06	79.5	38.1
31.0	7.6	65.5	1.62	1.59	1.94	79.9	41.4
31.4	7.4	60.3	1.8	2.11	2.2	73.7	36.0
26.9	6.7	73.2	1.89	1.77	1.96	88.9	34.8
30.0	8.6	72.8	1.95	1.9	1.73	87.0	35.1
25.0	6.4	36.0				46.5	
36.1	9.2	83.8				90.8	
36.0	7.7	80.3				88.0	
31.9	7.3	78.8				89.3	
30.5	7.8	79.8				90.9	
31.5	7.6	60.5	1.95	2.15	2.37	73.9	39.6
29.7	7.2	71.3				85.7	
29.1	7.4	53.2				68.8	
26.5	7.9	67.8				86.4	
24.9	7.8	71.9				90.0	
25.8	7.7	48.3				69.1	
24.7	7.3	53.0				76.3	

The data represent a wide range in circuit operations, with feed ash ranging from 25% to 36% and recoveries varying between 46% and 91%. Figure 1 shows a plot of the flotation circuit data illustrating the trend in energy recovery versus clean coal ash. In addition to the average trend line, a second curve depicts the assumed grade/recovery curve for the case when the flotation feed ash content is 20% (ash content of the project sample). Using this low-ash coal feed grade/recovery curve, the projected performance of the existing flotation cells is 85% energy recovery at a clean coal ash content of 7.5%.

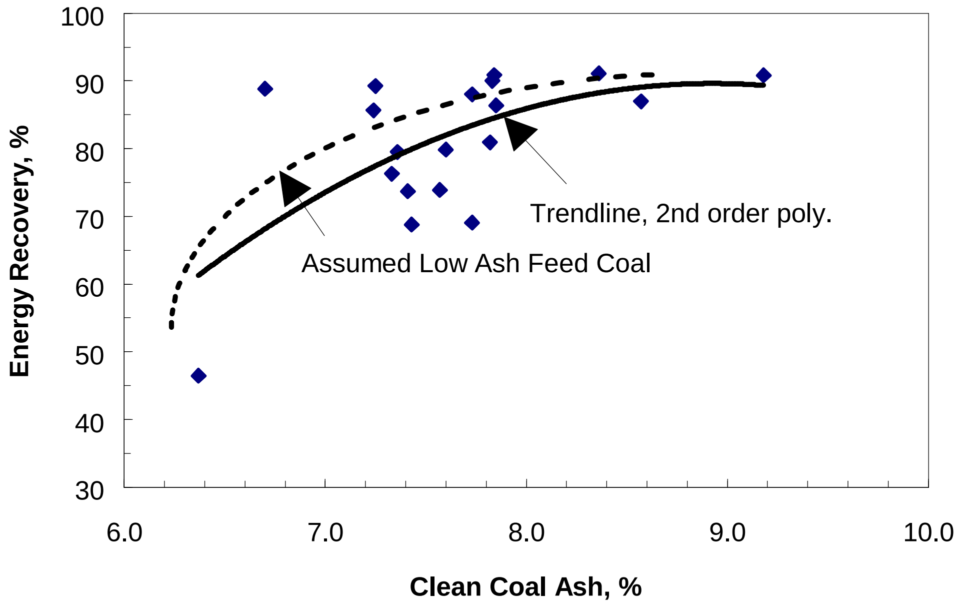

Figure 1. Historical Flotation Grade/Recovery Curve

4.2 Advanced Flotation Circuit Material Balances

Material balance estimates of single- and two-stage flotation circuits were developed based on information in the literature, discussions with the equipment vendors, and the characterization test data (batch flotation tests and centrifuge float/sink analyses).

A review of the literature on advanced flotation cell operations indicated that:

- Properly applied wash water was effective in removing entrained ash from the froth.
- Product ash can approach the ash level measured by float 1.6 specific gravity (centrifuge sink/float method).

Estimates of the performance for both single-stage and two-stage flotation circuits were derived from consideration of the washability properties of the raw coal sample and bench-scale flotation test results as given in Section 3.3. Table 17 and Table 18 list the relevant data for these tests and the assumed performance for single-stage operation and for the first stage of a two-stage circuit, respectively. At this point, the overall performance of the two-stage circuit was assumed to be the same as that of the single-stage circuit.

Theoretically, the wash water is set in excess of the water carry-over by the froth to remove all of the process water from the froth and establish a net flow of wash water to the flotation tailings stream, i.e., negative bias.

Table 17. Estimated Single-Stage Flotation Performance

	Raw Coal Washability Float 1.6 SG	Laboratory Flotation Test	Assumed Single-Stage Advanced Flotation Circuit Performance
Weight Yield, %	80.5	77.7	76.6
Btu Recovery, %	92.5	91.0	91.0
Clean Coal Ash, %	5.9	4.4	5.0
Clean Coal Sulfur, %	0.94	1.11	1.0

Table 18. Estimated First-Stage Flotation Performance

	Raw Coal Washability Float 1.4 SG	Laboratory Flotation Test	Assumed First-Stage Advanced Flotation Circuit Performance
Weight Yield, %	59.7	64.7	60.0
Btu Recovery, %	70.6	76.1	72.0
Clean Coal Ash, %	4.17	4.0	4.0
Clean Coal Sulfur, %	0.95	1.09	1.0

The assumptions required to complete a material balance for the single-stage and two-stage circuits are given in Table 19. The feed conditions are taken from the plant flowsheet and the coal quality values are selected to be compatible with the project raw coal sample.

Table 19. Plant Flotation Circuit Assumptions

Feed Rate, tph	76
Flow Rate, gpm	9,000
Feed % Solids	3.3
Feed Ash, %	20
Feed Sulfur, %	1.1

The plant feed conditions and circuit performance assumptions (Table 17, Table 18, and Table 19) were used to derive material balance estimates for the single-stage circuit, given in Table 20, and for a two-stage configuration, given in Table 21.

The important features of the assumed material balances are:

- Feed percent solids is 3.3%
- Overall product ash is 5%
- Energy recovery is 91%
- Second-stage feed ash is 44%
- Second-stage feed percent solids is 1.4%
- Second-stage flow rate is approximately equal to first-stage flow rate.

Table 20. Estimated Single-Stage Material Balance

	Solids, tph	Solids, Wt. %	Water, tph	Slurry, tph	Slurry Density gm/ml	Slurry Flow Rate, gpm	Ash, %	Sulfur, %
Feed	76	3.35	2193	2269	1.008	9000	20.0	1.1
Wash Water			250	250	1.000	1000		
Product	58	20	233	291	1.053	1107	5.0	1.0
Tailings	18	0.80	2210	2228	1.002	8893	69.2	1.4

Table 21. Estimated Two-Stage Flotation Material Balance

	Solids, tph	Solids, Wt. %	Water, tph	Slurry, tph	Slurry Density gm/ml	Slurry Flow Rate, gpm	Ash, %	Sulfur, %
1st-stage balance								
Feed	76	3.3	2,193	2,269	1.008	9,000	20.0	1.1
Wash Water			200	200	1.000	800		
Product	46	20.0	182	228	1.053	866	4.0	1.0
Tailings	30	1.4	2,211	2,241	1.003	8,934	44.0	1.3
2nd-stage Balance								
Feed	30	1.4	2,211	2,241	1.003	8,934	44.0	1.3
Wash Water			75	75	1.000	300		
Product	13	20.0	51	63	1.053	240	8.6	1.0
Tailings	18	0.8	2,235	2,253	1.002	8,993	69.2	1.4
Combined Product	58		233	291	1.053	1,107	5.00	1.0

5.0 BENCH-SCALE TESTS

5.1 Introduction

As described in Section 4, coal characterization flotation tests and washability analyses conducted prior to bench-scale testing indicated that a product containing less than 5% ash could be achieved with high energy recovery. The flotation cell vendors were informed of these results before starting the bench-scale test work and were asked to achieve a minimum energy recovery of 85% at a product ash of 5% for a single-stage operation. The second-stage performance target (tailings sample) was set at production of a 5-10% ash product at a minimum 70% energy recovery. This would provide a total energy recovery of 90% or more in the two-stage operation.

The vendors were also instructed to determine cell operating conditions to produce a low-ash first-stage product at maximum capacity and lower-than-acceptable total energy recovery. A grade/recovery relationship for a second-stage operation was established using the plant tailings sample in the column cells. By determining the conditions for single-stage and two-stage flotation operations, a total grade/recovery relationship for the two stages could be calculated.

During the test work, a test engineer visited each test site to inspect the work in progress and to assure that appropriate QA/QC measures were adopted during test and analytical work. Flow rates, equipment calibration, and process calculations were verified to assure that the reported values were accurate. Cell operations were discussed with the vendors, and their recommendations for equipment scale-up were obtained. Test work on the Outokumpu HG tank cell was conducted in the coal preparation plant under the supervision of a project test engineer. The dimensions of the cells used for the bench-scale test work are given in Table 1. The bench-scale tests conducted for each flotation machine, along with the results obtained, are summarized in this section.

5.2 Jameson Cell

All bench-scale tests for this cell used only feed coal. The test work was conducted in two sequences. First, a series of 19 single-stage tests and 3 two-stage tests was completed, primarily to quantify the importance of major operating parameters (parametric studies). A 6-inch diameter cell was used for this series and the equipment configuration such as the downcomer diameter and orifice size was set to conform to sizes (24.5 mm and 3 mm, respectively) used for coal flotation in Australia.

A second series of tests was completed at very high feed flow rates in order to evaluate the Jameson cell for first-stage operations. A 4-inch diameter cell was used for these tests in order to minimize sample usage.

The major process parameters tested were:

- Reagent dosage
- Froth depth
- Feed rate
- Two-stage processing.

All tests were carried out on a semi-batch basis. Coal slurry was batched to a holding tank and agitated with a mixer. The feed slurry was also recirculated with a pump. Fuel oil was added to the feed coal batch and mixed (conditioned) for five minutes before the start of testing. Frother was added directly into the feed pipe. Air was adjusted to produce a stable froth in accordance with previous process parameter settings used for treating coal. The cell was operated for at least 600 seconds (10 minutes) until steady state was achieved, after which product and tailings samples were collected simultaneously. For each set of tests, a feed sample was taken prior to the start of testing.

During testing, it was observed that the downcomer operation was very consistent and the partial vacuum developed in it remained stable. Similarly, the froth depth was also consistent and did not vary more than ±0.635 cm (±0.25 inches). The froth achieved was dense and viscous with a small bubble structure. However, the discharge from the cell was continuous and consistent.

The bench-scale tests conditions are shown in Table 22 and results are shown in Table 23. The various scale-up parameters for these tests are shown in Table 24. This table presents the Jameson cell test conditions after conversion to superficial velocity and mass loading values for purposes of comparison to the other flotation cells. Since the flow rate to the Jameson cell is set by the downcomer jet action, the feed mass flow rate was tested over a narrow range of 1.14 to 1.44 tph/m^2 during the parametric tests (1.9 to 2.4 gm/min/cm^2) with a feed superficial velocity of about 1.5-1.6 cm/s (3.0-3.2 ft/min) (calculation based on froth tank area and feed flow rate). The corresponding froth mass flow rate was 0.6-1.02 tph/m^2 (1.0-1.7 gm/min/cm^2).

The prefixes designating test types in these tables stand for the following:

- VR: Reagent dosage variation
- LF: Low frother
- VF: Variable froth depth tests
- HT, DT: Feed rate variability
- TS: Two-stage tests
- HV: Series 2 tests with high volumetric feed rates.

Table 22. Bench-Scale Test Conditions for Jameson Cell

Test Number	Feed Flow Rate gpm	Feed Flow Rate m^3/s x 10^{-3}	Solids %	Mass Flow Rate gm/min	Mass Flow Rate Kg/s	Fuel Oil lb/ton	Fuel Oil Kg/t	Frother lb/ton	Frother Kg/t	Froth Depth in	Froth Depth m	Wash Water gpm	Wash Water m^3/s x 10^{-3}	Air l/min	Air m^3/s x 10^{-3}
15.2 cm (6 inch) diameter Jameson cell															
VR-1	3.17	0.20	2.96	355	0.0059	1.33	0.67	0.67	0.34	15	0.38	0.50	0.032	NA	NA
VR-2	3.17	0.20	2.96	355	0.0059	1.67	0.84	0.80	0.40	18	0.46	0.50	0.032	NA	NA
VR-3	3.17	0.20	2.96	355	0.0059	2.00	1.00	1.00	0.50	20	0.51	0.50	0.032	NA	NA
VR-4	3.17	0.20	2.96	355	0.0059	2.33	1.17	1.17	0.59	21	0.53	0.50	0.032	NA	NA
VR-5	3.17	0.20	2.96	355	0.0059	2.67	1.34	1.33	0.67	22	0.56	0.50	0.032	NA	NA
VR-6	3.17	0.20	2.96	355	0.0059	3.00	1.50	1.50	0.75	22	0.56	0.50	0.032	NA	NA
VF-1	3.43	0.22	2.91	378	0.0063	2.67	1.34	1.33	0.67	23	0.58	0.50	0.032	NA	NA
VF-2	3.43	0.22	2.91	378	0.0063	2.67	1.34	1.33	0.67	17	0.43	0.50	0.032	NA	NA
VF-3	3.43	0.22	2.91	378	0.0063	2.67	1.34	1.33	0.67	13	0.33	0.50	0.032	NA	NA
VF-4	3.43	0.22	2.91	378	0.0063	2.67	1.34	1.33	0.67	10	0.25	0.50	0.032	NA	NA
VF-5	3.43	0.22	2.91	378	0.0063	2.67	1.34	1.33	0.67	7	0.18	0.50	0.032	NA	NA
HT-1	3.96	0.25	2.91	436	0.0073	2.67	1.34	1.33	0.67	5	0.13	0.50	0.032	NA	NA
HT-2	3.96	0.25	2.91	436	0.0073	2.67	1.34	1.33	0.67	4	0.1	0.50	0.032	NA	NA
DT-1	3.17	0.20	2.71	325	0.0054	2.67	1.34	1.33	0.67	7	0.18	0.50	0.032	NA	NA
DT-2	3.17	0.20	2.71	325	0.0054	2.67	1.34	1.33	0.67	5	0.13	0.50	0.032	NA	NA
LF-1	3.17	0.20	2.94	353	0.0059	3.00	1.50	1.00	0.50	6	0.15	0.50	0.032	NA	NA
LF-2	3.17	0.20	2.94	353	0.0059	3.50	1.75	0.80	0.40	6	0.15	0.50	0.032	NA	NA
LF-3	3.17	0.20	2.94	353	0.0059	4.00	2.00	0.50	0.25	2	0.05	0.50	0.032	NA	NA
TS-1	3.96	0.25	2.89	433	0.0072	2.67	1.34	1.33	0.67	5	0.13	0.50	0.032	NA	NA
TS-2*	3.30	0.21	0.91	114	0.0019	0.00	0.00	0.00	0.00	6	0.15	0.50	0.032	NA	NA
TS-3*	3.30	0.21	0.91	114	0.0019	1.30	0.65	0.80	0.40	6	0.15	0.50	0.032	NA	NA
TS-4*	3.30	0.21	0.91	114	0.0019	3.50	1.75	2.10	1.05	6	0.15	0.50	0.032	NA	NA
10.2 cm (4 inch) diameter Jameson cell															
HVR-1	5.87	0.37	2.67	593	0.0099	2.20	1.10	1.13	0.57	22	0.56	1.00	0.063	NA	NA
HVR-2	5.87	0.37	2.67	593	0.0099	1.70	0.85	0.85	0.43	19	0.48	1.00	0.063	NA	NA
HVR-3	5.87	0.37	2.67	593	0.0099	1.70	0.85	0.85	0.43	16	0.41	1.00	0.063	NA	NA
HVR-4	5.87	0.37	2.67	593	0.0099	1.70	0.85	0.85	0.43	6	0.15	1.00	0.063	NA	NA
HVTS-1	5.87	0.37	2.71	602	0.0101	2.00	1.00	0.75	0.38	22	0.56	1.00	0.063	NA	NA
HVTS-2*	5.87	0.37	1.03	229	0.0038	0.00	0.00	0.00	0.00	6	0.15	0.50	0.032	NA	NA
HVTS-3*	5.87	0.37	1.03	229	0.0038	0.20	0.10	0.00	0.00	13	0.33	0.50	0.032	NA	NA
HVTS-4*	5.87	0.37	1.03	229	0.0038	0.20	0.10	0.00	0.00	3	0.08	0.50	0.032	NA	NA

* Two stage tests

Table 23. Bench-Scale Test Results for Jameson Cell

	Feed			Product			Tailings			Analysis				
Test Number	Ash %	Sulfur %	Pyr. S %	Ash %	Sulfur %	Pyr. S %	Ash %	Sulfur %	Pyr. S %	Yield, %	CMR, %	Ash Rej %	TSR %	PSR %
15.2 cm (6 inch) diameter Jameson cell														
VR-1	20.2			3.6	0.98		38.4			52	63	91		
VR-2	20.2			3.7			46.1			61	74	89		
VR-3	20.2			3.9			51.1			65	79	87		
VR-4	20.2	1.00	0.49	4.2	0.97	0.25	55.9	1.10	1.08	69	83	86	33.0	64.8
VR-5	20.2	1.00		3.7	1.01		53.9			67	81	88	32.2	
VR-6	20.2			4.0			45.7			61	74	88		
VF-1	20.4	1.07	0.57	3.7	0.92	0.24	46.5	1.20	1.01	61	74	89	47.6	74.3
VF-2	20.4			3.8			51.8			65	79	88		
VF-3	20.4			3.9			54.5			67	81	87		
VF-4	20.4			4.0			57.9			70	84	87		
VF-5	20.4			4.0			60.1			71	85	86		
HT-1	19.5			4.1	1.02		60.7			73	87	85		
HT-2	19.5			4.2			67.3			76	90	84		
DT-1	21.5	1.01	0.53	4.5	0.96	0.27	56.0	1.19	1.12	67	82	86	36.3	65.9
DT-2	21.5	1.01		4.7	1.02		61.4			70	85	85	29.0	
LF-1	20.0			4.4			49.9			66	79	86		
LF-2	20.0			4.0			53.6			68	81	86		
LF-3	20.0			7.2			79.8			82	96	70		
TS-1	19.5			4.1	1.04		60.7			73	87	85		
TS-2	57.9			7.5			80.8			31	69	96		
TS-3	57.9			8.1			82.7			33	73	95		
TS-4	57.9			7.9			81.9			32	71	96		
10.2 cm (4 inch) diameter Jameson cell														
HVR-1	37.6			3.7			66.0			46	70	96		
HVR-2	37.6			4.3			74.1			52	80	94		
HVR-3	37.6			4.0			68.3			48	73	95		
HVR-4	37.6			5.3			51.8			31	46	96		
HVTS-1	20.0			3.8			45.0			61	73	89		
HVTS-2	45.0			4.7			48.3			8	13	99		
HVTS-3	45.0			5.1			59.5			27	46	97		
HVTS-4	45.0			7.8			58.7			27	45	95		

* Two stage tests

Table 24. Jameson Cell: Superficial Velocities and Mass Loadings

			Superficial Velocities						Mass Loadings			
	Mean Residence Time		Feed		Wash Water		Air		Feed		Froth	
Test Number	min	s	cm/s	m/s	cm/s	m/s	cm/s	m/s	gm/min/ cm^2	tph/ m^2	gm/min/ cm^2	tph/ m^2
15.2 cm (6 inch) diameter Jameson cell												
VR-1	1.27	76.41	1.10	0.011	0.17	0.002	NA	NA	1.95	1.17	1.02	0.61
VR-2	1.16	69.47	1.10	0.011	0.17	0.002	NA	NA	1.95	1.17	1.19	0.71
VR-3	1.08	64.83	1.10	0.011	0.17	0.002	NA	NA	1.95	1.17	1.28	0.77
VR-4	1.04	62.52	1.10	0.011	0.17	0.002	NA	NA	1.95	1.17	1.34	0.81
VR-5	1.00	60.20	1.10	0.011	0.17	0.002	NA	NA	1.95	1.17	1.31	0.78
VR-6	1.00	60.20	1.10	0.011	0.17	0.002	NA	NA	1.95	1.17	1.19	0.72
VF-1	0.89	53.50	1.19	0.012	0.17	0.002	NA	NA	2.07	1.24	1.26	0.76
VF-2	1.11	66.34	1.19	0.012	0.17	0.002	NA	NA	2.07	1.24	1.36	0.81
VF-3	1.25	74.90	1.19	0.012	0.17	0.002	NA	NA	2.07	1.24	1.40	0.84
VF-4	1.36	81.32	1.19	0.012	0.17	0.002	NA	NA	2.07	1.24	1.44	0.86
VF-5	1.46	87.74	1.19	0.012	0.17	0.002	NA	NA	2.07	1.24	1.47	0.88
HT-1	1.33	79.70	1.37	0.014	0.17	0.002	NA	NA	2.39	1.44	1.74	1.04
HT-2	1.36	81.56	1.37	0.014	0.17	0.002	NA	NA	2.39	1.44	1.81	1.09
DT-1	1.58	94.94	1.10	0.011	0.17	0.002	NA	NA	1.78	1.07	1.20	0.72
DT-2	1.66	99.57	1.10	0.011	0.17	0.002	NA	NA	1.78	1.07	1.25	0.75
LF-1	1.62	97.25	1.10	0.011	0.17	0.002	NA	NA	1.94	1.16	1.27	0.76
LF-2	1.62	97.25	1.10	0.011	0.17	0.002	NA	NA	1.94	1.16	1.31	0.79
LF-3	1.78	106.51	1.10	0.011	0.17	0.002	NA	NA	1.94	1.16	1.59	0.96
TS-1	1.33	79.70	1.37	0.014	0.17	0.002	NA	NA	2.38	1.43	1.73	1.04
TS-2	1.56	93.42	1.14	0.011	0.17	0.002	NA	NA	0.62	0.37	0.19	0.12
TS-3	1.56	93.42	1.14	0.011	0.17	0.002	NA	NA	0.62	0.37	0.21	0.12
TS-4	1.56	93.42	1.14	0.011	0.17	0.002	NA	NA	0.62	0.37	0.20	0.12
10.2 cm (4 inch) diameter Jameson cell												
HVR-1	0.24	14.45	4.57	0.046	0.78	0.008	NA	NA	7.32	4.39	3.34	2.00
HVR-2	0.27	16.12	4.57	0.046	0.78	0.008	NA	NA	7.32	4.39	3.83	2.30
HVR-3	0.30	17.78	4.57	0.046	0.78	0.008	NA	NA	7.32	4.39	3.50	2.10
HVR-4	0.39	23.34	4.57	0.046	0.78	0.008	NA	NA	7.32	4.39	2.23	1.34
HVTS-1	0.24	14.45	4.57	0.046	0.78	0.008	NA	NA	7.43	4.46	4.50	2.70
HVTS-2	0.39	23.34	4.57	0.046	0.39	0.004	NA	NA	2.82	1.69	0.21	0.13
HVTS-3	0.32	19.45	4.57	0.046	0.39	0.004	NA	NA	2.82	1.69	0.75	0.45
HVTS-4	0.42	25.01	4.57	0.046	0.39	0.004	NA	NA	2.82	1.69	0.76	0.46

* Two stage tests

The results of various series of tests are discussed in the following sections.

5.2.1 Parametric Studies: Discussion of Results

The main conclusions of the parametric tests are that higher recoveries are achieved by:

- Increasing reagent dosages
- Reducing the froth depth, or
- Reprocessing the tailings in a second stage.

These conclusions are graphically illustrated in Figure 2

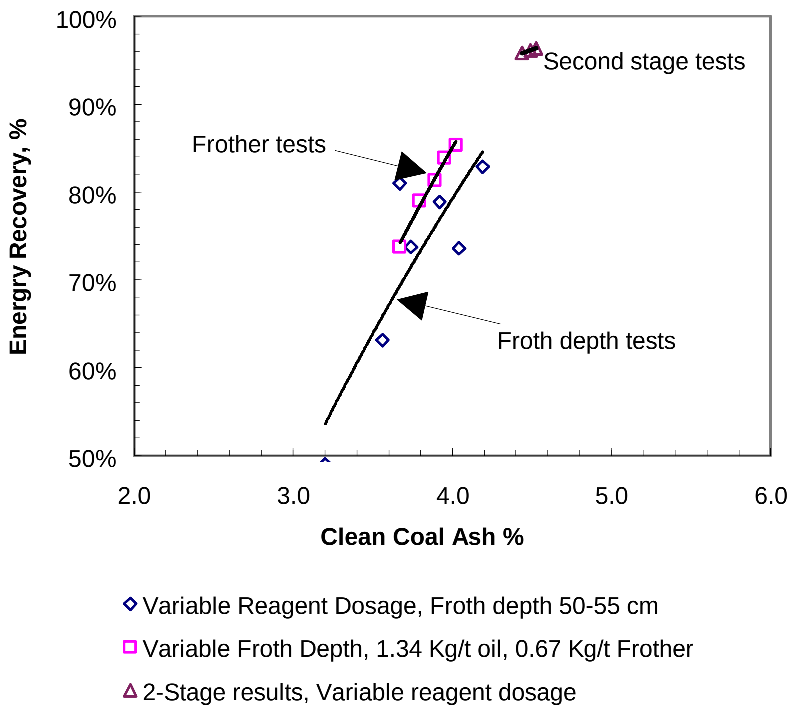

Figure 2. Parametric Test Results for the Jameson Cell

Test results showed that the grade/recovery curve for this case is very steep, i.e., a large increase in recovery can be realized with only a small increase in the product ash content. This is indicative of a high degree of liberation. It can be seen in Figure 3 that product ash variation from about 3.5% to 4.4% can mean a shift in energy recovery from 65% to about 85%. Figure 4 shows the grade/recovery relationship in terms of energy recovery and the total sulfur of the clean coal product obtained after processing in the Jameson cell. This relationship also shows a similar trend in that a fairly large shift in energy recovery can occur without much impact on product sulfur. The reason for this phenomenon is that most of the sulfur remaining in the froth is organic, which does not change with recovery.

The relationship of ash and sulfur rejection with energy recovery is shown in Figure 5 and Figure 6. It can be seen that at 85% energy recovery, ash and sulfur rejections are 85% and 30% respectively.

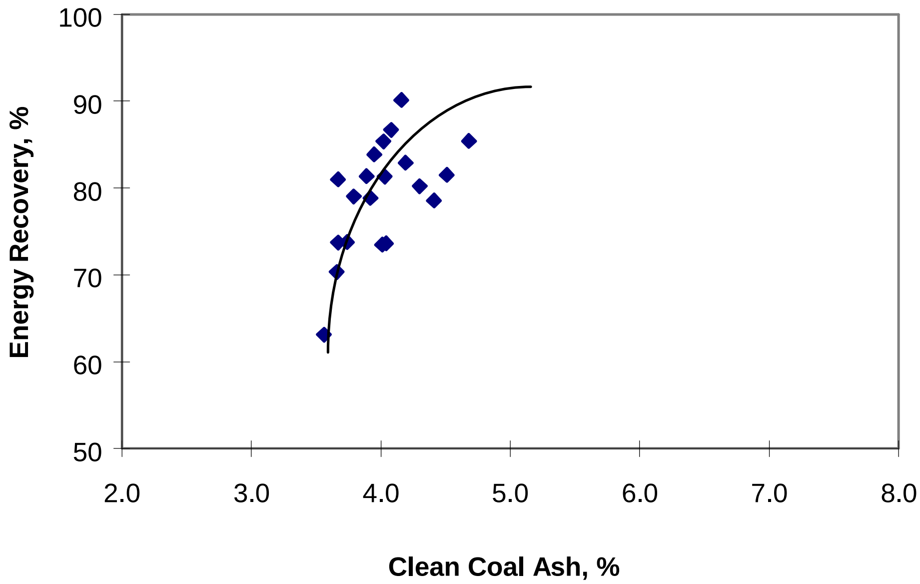

Figure 3. Jameson Cell: Energy Recovery vs. Clean Coal Ash

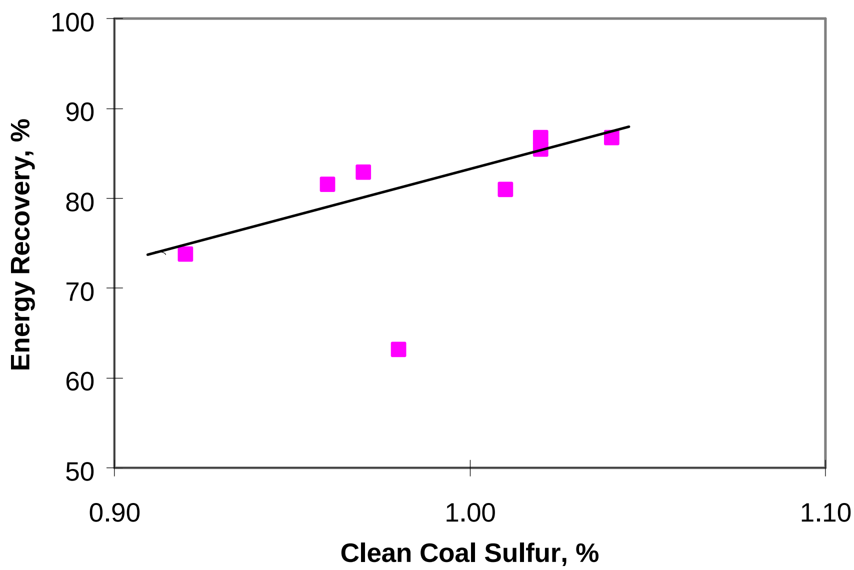

Figure 4. Jameson Cell: Energy Recovery vs. Clean Coal Sulfur

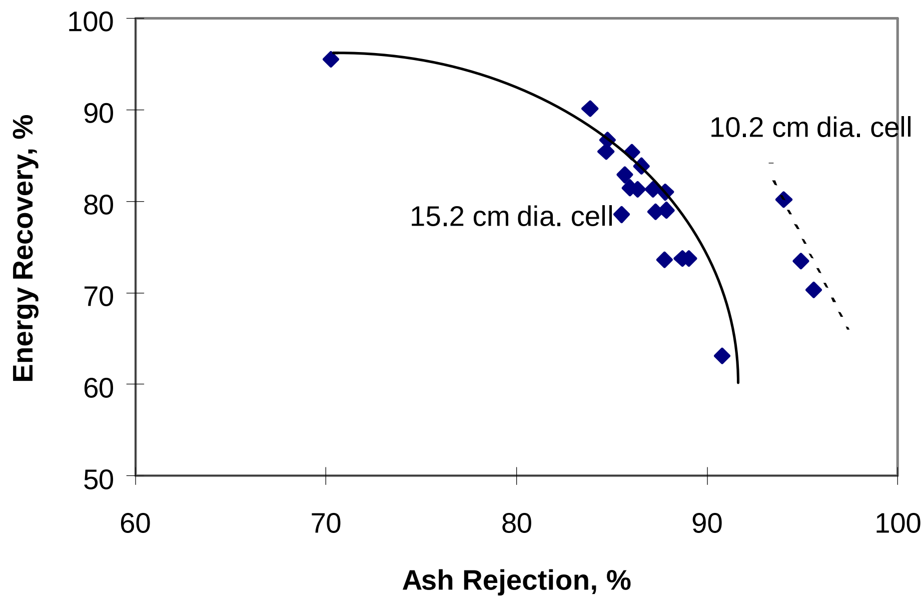

Figure 5. Jameson Cell: Energy Recovery vs. Ash Rejection

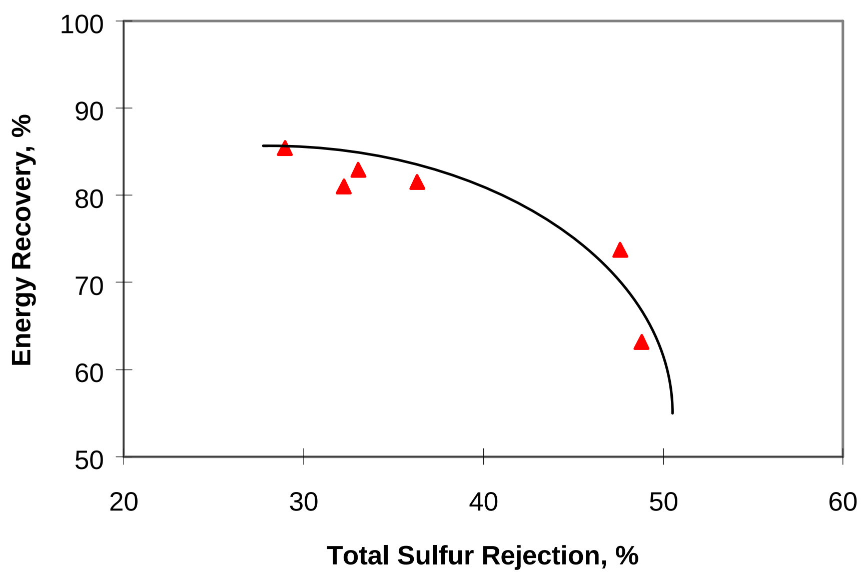

Figure 6. Jameson Cell: Energy Recovery vs. Sulfur Rejection

5.2.2 High-Capacity Tests

Although the parametric tests indicated that good process separation efficiency could be realized, the capacity achieved was perceived to be low, especially for first-stage operation in a two-stage flotation circuit. A series of eight high-capacity tests was conducted to determine whether the separation efficiency could be maintained at high mass loadings in the froth. A 4-inch diameter test cell was used for these tests as a means of conserving the coal sample.

All relevant data for these tests are shown in Table 22, Table 23, and Table 24. The tests are prefixed with "HV." The high-capacity tests were run at four times the flow rate per cross-sectional area of the original tests for a superficial feed velocity of 4.57 cm/s. The wash water was proportioned to the expected froth mass loading. A deeper froth bed was used to provide sufficient time for removal of entrained ash. Lower reagent dosages were used for economical operations. The results indicate that low product ash could still be achieved under these conditions. The final test using the original project coal produced a 3.8% ash product with 73% energy recovery. The froth mass loading was 4.5 gm/min/cm^2, and showed that much higher flow rates are possible when this cell is used in a first-stage application.

5.2.3 Recommended Operating Conditions

Based on the parametric test work, the recommended conditions for the Jameson cell are given in Table 25 for single-stage operation and in Table 26 for the first-stage application in a two-stage process.

Table 25. Jameson Cell: Recommended Operating Conditions, Single-Stage Operation

Parameter	*Value*
Feed velocity	1.2 cm/s (2.3 ft/min)
Frother to fuel oil ratio	1:2 to 1:3
Total reagent dosage	2 kg/t (4 lb/ton)
Froth depth	15.2 cm (6 inch)
Wash water flow rate	0.20 cm/s (0.4 ft/min)

Table 26. Jameson Cell: Recommended Operating Conditions, First-Stage Operation

Parameter	*Value*
Feed velocity	4.5 cm/s (8.9 ft/min)
Frother to fuel oil ratio	1:2.6
Total reagent dosage	1.38 kg/t (2.75 lb/ton)
Froth depth	56 cm (22 inch)
Wash water flow rate	0.78 cm/s (1.6 ft/min)

5.3 Outokumpu Cell

A total of 15 tests were conducted on the Outokumpu HG tank cell at the coal preparation plant as part of the bench-scale test work. The test conditions and results are shown in Table 27 and Table 28. The scale-up parameters for this cell are shown in Table 29. This table provides the test conditions for the Outokumpu cell after conversion to superficial velocity and mass loading values for purposes of comparison. The feed superficial velocity varied between 1.0 and 2.2 cm/s with a corresponding feed mass loading of 1.02 to 2.28 tph/m^2 (1.7 to 3.8 gm/min/cm^2). The froth loading was as high as 1.8 tph/m^2 (3 gm/min/cm^2); however, poor process efficiency was obtained at this loading. A froth loading of 1.08 tph /m^2 (1.8 gm/min/cm^2) achieved acceptable results.

A slipstream of the minus 150µ (100-mesh) classifying cyclone overflow was diverted to the cell. Reagents were added to the feed slurry using metering pumps. The water-soluble frother was diluted 1:10 to improve metering accuracy.

The major parameters tested were:

- Reagent dosage
- Wash water
- Froth depth
- Feed slurry flow rate or residence time.

After preliminary testing, the superficial air velocity was set to approximately 2.3-2.4 cm/s (4.6-4.8 ft/min) in accordance with vendor recommendations. The cell was operated for a minimum of 900 seconds (15 minutes) between tests. Product and tailings samples were taken simultaneously, and feed samples were collected immediately following the collection of product samples. The Outokumpu cell behaved differently from the other three cells in terms of froth mobility which showed a great deal of sensitivity to oil. During the first three tests conducted using 0.54-0.72 kg/t (1.08-1.45 lb/t) of fuel oil, the froth was viscous and did not discharge easily. Product ash contents were between 9.2 and 10% with energy recoveries in the 73-79% range.

In order to alleviate this difficulty, tests 4 through 11 were carried out with no oil addition. This had the desired effect of reducing froth viscosity but also led to a considerable loss of energy recovery. Though some improvement was noticed in the product ashes, they still remained well above the 5% target.

The last set of four tests used about half of the oil used in the first tests. This improved the energy recovery, but still gave unacceptable product ashes.

The relationship of energy recovery with product ash and sulfur contents is shown in Figure 7 and Figure 8. Figure 9 and Figure 10 show the effect of energy recovery on ash and sulfur rejections. It can be seen that the Outokumpu cell did not meet the project targets. However, it must be recognized that it was run using an actual plant slipstream and its performance may have been somewhat affected by the changing behavior of the plant feed.

Table 27. Bench-Scale Test Conditions for Outokumpu HG Tank Cell

	Feed Flow Rate		Solids	Mass Flow Rate		Fuel Oil		Frother		Froth Depth		Wash Water		Air	
Test Number	gpm	$m^3/s \times 10^{-3}$	%	gm/ min	Kg/ s	lb/ ton	Kg/ t	lb/ ton	Kg/ t	in	m	gpm	$m^3/s \times 10^{-3}$	cfm	$m^3/s \times 10^{-3}$
1	11	0.69	2.85	1187	0.02	1.45	0.72	1.12	0.56	2.5	0.06	2.00	0.13	3.4	1.60
2	16	1.01	2.60	1575	0.03	1.09	0.55	0.84	0.42	2.5	0.06	1.00	0.06	3.5	1.65
3	16	1.01	2.62	1587	0.03	1.08	0.54	0.58	0.29	2.5	0.06	1.00	0.06	3.5	1.65
4	25	1.58	2.54	2404	0.04	0.00	0.00	0.96	0.48	5.0	0.13	0.00	0.00	3.5	1.65
5	25	1.58	2.59	2451	0.04	0.00	0.00	0.94	0.47	5.0	0.13	3.00	0.19	3.5	1.65
6	20	1.26	2.59	1961	0.03	0.00	0.00	1.18	0.59	5.0	0.13	3.25	0.21	3.6	1.70
7	20	1.26	2.63	1991	0.03	0.00	0.00	1.45	0.73	5.0	0.13	3.00	0.19	3.6	1.70
8	20	1.26	2.63	1991	0.03	0.00	0.00	1.45	0.73	5.0	0.13	0.00	0.00	3.6	1.70
9	20	1.26	3.01	2279	0.04	0.00	0.00	1.44	0.72	5.0	0.13	0.00	0.00	3.6	1.70
10	20	1.26	3.01	2279	0.04	0.00	0.00	1.44	0.72	5.3	0.13	3.00	0.19	3.6	1.70
11	25	1.58	3.01	2849	0.05	0.00	0.00	1.01	0.51	5.3	0.13	3.00	0.19	3.6	1.70
12	25	1.58	2.66	2517	0.04	0.51	0.26	1.15	0.57	5.0	0.13	3.00	0.19	3.6	1.70
13	25	1.58	2.66	2517	0.04	0.46	0.23	1.30	0.65	5.0	0.13	3.00	0.19	3.6	1.70
14	25	1.58	2.90	2744	0.05	0.52	0.26	1.19	0.60	5.0	0.13	3.00	0.19	3.6	1.70
15	25	1.58	2.90	2744	0.05	0.47	0.24	1.19	0.60	5.0	0.13	3.00	0.19	3.6	1.70

Table 28. Bench-Scale Test Results for Outokumpu HG Tank Cell

	Feed		Product		Tailings		Analysis			
Test Number	Ash %	Sulfur %	Ash %	Sulfur %	Ash %	Sulfur %	Yield, %	CMR, %	Ash Rej %	TSR %
1	30.4	1.15	9.2	1.33	57.4	1.06	56	73	83	35
2	31.2	1.13	9.6	1.29	61.6	1.05	58	77	82	33
3	30.0	1.13	10.0	1.28	61.9	0.98	62	79	79	30
4	17.4	1.26	11.8	1.21	26.9	1.29	63	67	58	40
5	19.5	1.19	9.6	1.14	31.4	1.18	55	61	73	48
6	19.5	1.19	7.3	1.20	37.5	1.24	59	69	78	40
7	19.9	1.23	8.4	1.22	34.0	1.25	55	63	77	45
8	19.9	1.23	14.4	1.27	31.6	1.34	68	73	51	30
9	19.4	1.33	8.5	1.27	32.9	1.40	56	63	76	47
10	19.4	1.33	7.5	1.22	33.7	1.29	55	63	79	50
11	19.4	1.33	14.0	1.25	36.4	1.26	76	81	45	29
12	20.5	1.25	16.0	1.32	38.7	1.32	80	85	37	15
13	20.5	1.25	12.5	1.30	39.9	1.32	71	78	57	26
14	20.6	1.27	11.3	1.23	41.3	1.22	69	77	62	33
15	20.6	1.27	7.9	1.21	37.4	1.17	57	66	78	46

Table 29. Outokumpu HG Tank Cell: Superficial Velocities and Mass Loadings

			Superficial Velocities						Mass Loadings			
	Mean Residence Time		Feed		Wash Water		Air		Feed		Froth	
Test Number	min	s	cm/s	m/s	cm/s	m/s	cm/s	m/s	gm/min/ cm^2	tph/ m^2	gm/min/ cm^2	tph/ m^2
1	1.31	78.67	0.96	0.010	0.18	0.002	2.23	0.022	1.65	0.99	0.92	0.55
2	0.90	54.09	1.40	0.014	0.09	0.001	2.29	0.023	2.18	1.31	1.28	0.77
3	0.90	54.09	1.40	0.014	0.09	0.001	2.29	0.023	2.20	1.32	1.36	0.81
4	0.58	34.62	2.19	0.022	0.00	0.000	2.29	0.023	3.33	2.00	2.09	1.25
5	0.58	34.62	2.19	0.022	0.26	0.003	2.29	0.023	3.40	2.04	1.86	1.12
6	0.72	43.27	1.75	0.018	0.28	0.003	2.36	0.024	2.72	1.63	1.62	0.97
7	0.72	43.27	1.75	0.018	0.26	0.003	2.36	0.024	2.76	1.66	1.52	0.91
8	0.72	43.27	1.75	0.018	0.00	0.000	2.36	0.024	2.76	1.66	1.88	1.13
9	0.72	43.27	1.75	0.018	0.00	0.000	2.36	0.024	3.16	1.90	1.76	1.05
10	0.72	43.27	1.75	0.018	0.26	0.003	2.36	0.024	3.16	1.90	1.73	1.04
11	0.58	34.62	2.19	0.022	0.26	0.003	2.36	0.024	3.95	2.37	3.01	1.80
12	0.58	34.62	2.19	0.022	0.26	0.003	2.36	0.024	3.49	2.09	2.81	1.68
13	0.58	34.62	2.19	0.022	0.26	0.003	2.36	0.024	3.49	2.09	2.47	1.48
14	0.58	34.6168	2.19	0.022	0.26	0.003	2.36	0.024	3.81	2.28	2.62	1.57
15	0.58	34.62	2.19	0.022	0.26	0.003	2.36	0.024	3.81	2.28	2.17	1.30

Figure 7 illustrates the grade/recovery curve for this cell under various conditions tested in terms of energy recovery and product ash, and Figure 8 illustrates the relationship between product sulfur and energy recovery achieved for this cell.

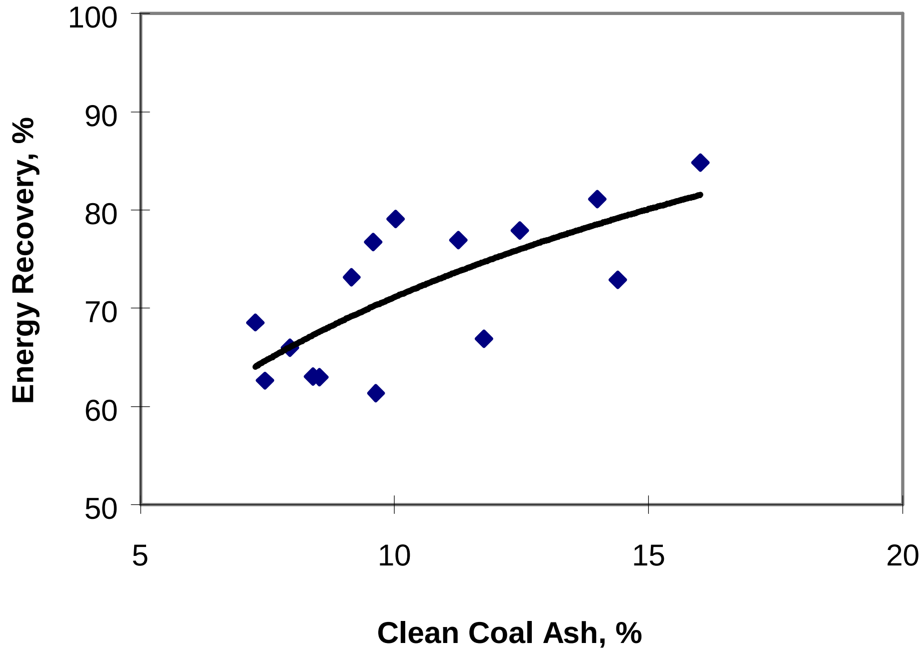

Figure 7. Outokumpu HG Tank Cell: Energy Recovery vs. Clean Coal Ash

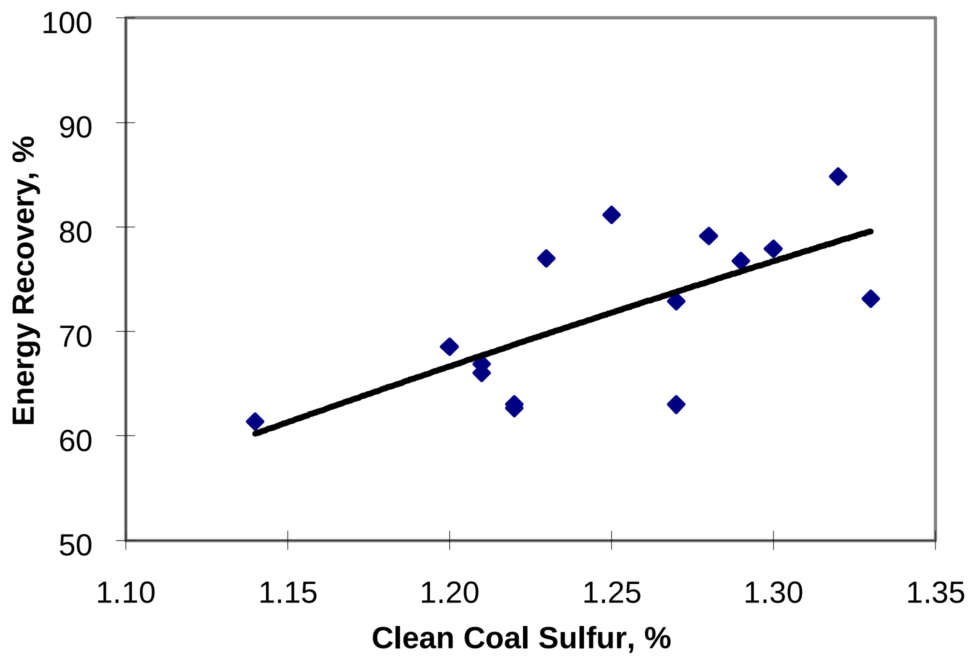

Figure 8. Outokumpu HG Tank Cell: Energy Recovery vs. Clean Coal Sulfur

The relationship of energy recovery with ash and total sulfur rejection is shown in Figure 9 and Figure 10. These figures show that the cell did not achieve recoveries of 85% or higher, and its ash and sulfur rejections were correspondingly lower.

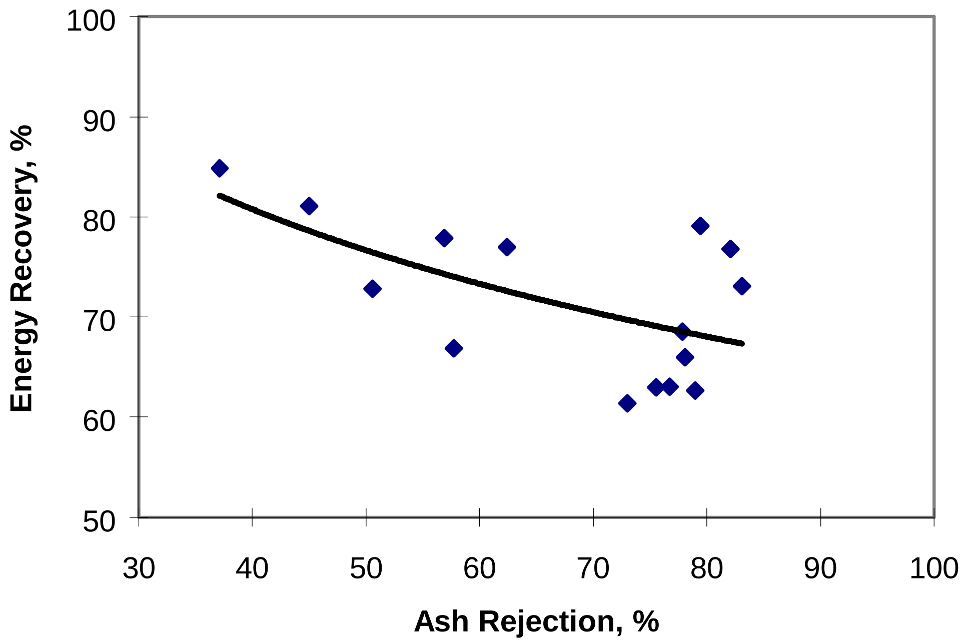

Figure 9. Outokumpu HG Tank Cell: Energy Recovery vs. Ash Rejection

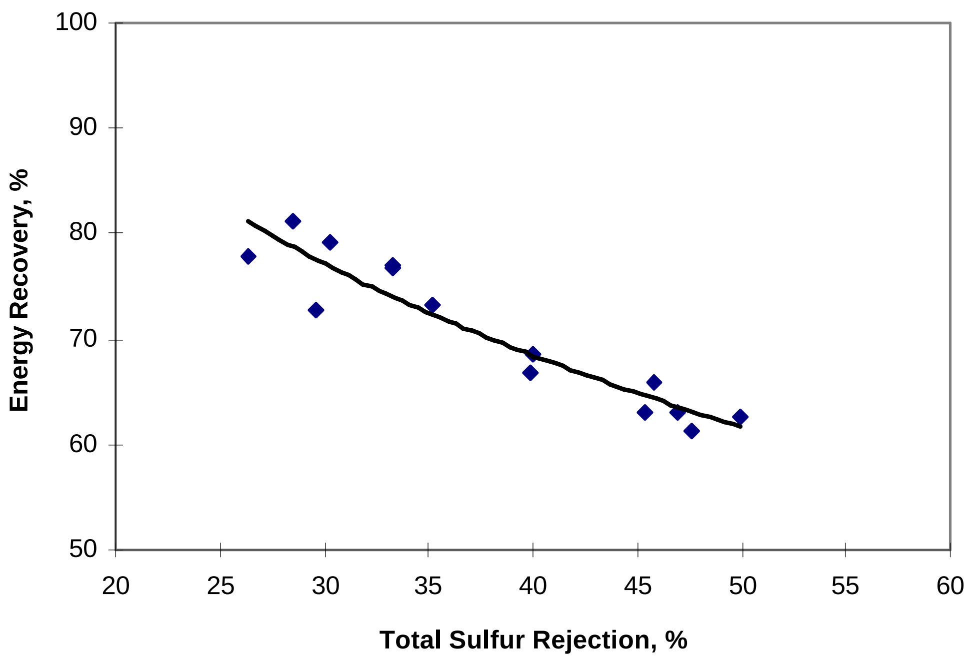

Figure 10. Outokumpu HG Tank Cell: Energy Recovery vs. Sulfur Rejection

5.3.1 Recommended Operating Conditions

The recommended conditions for the Outokumpu cell assuming first-stage operation are presented in Table 30. Recommended single-stage operation would use the same conditions except that the residence time would be increased from 1 minute to 2.5 minutes.

Table 30. Outokumpu Cell: Recommended First-Stage Operating Conditions

Parameter	Value
Residence Time	40-60 sec (0.67-1 min) per cell
Fuel Oil	0.1-0.25 kg/t (0.2-0.5 lb/ton)
Frother	0.5-0.65 kg/t (1.0-1.3 lb/ton)
Froth Depth	20.3 cm (8 inches)

5.4 Packed Column

Packed columns were tested and evaluated for use as single-stage units as well as second-stage units for cleaning the tailings. In order to assess their performance in these applications, the following test program was conducted:

- Twenty-nine parametric tests were carried out for the raw coal sample in a 3-in. diameter x 12-ft tall column (shown in Table 31 as A-1 through B-8-5).
- Four tests were conducted on the tailings in a 3-in. diameter x 12-ft tall column to evaluate its use as the second stage.

5.4.1 Raw Coal Parametric Tests

A total of 29 tests with the plant feed coal were conducted (shown in Table 31 as A-1 through B-8-5). The major parameters tested were:

- Feed slurry flow rate or residence time
- Reagent dosage
- Wash water
- Froth depth
- Aeration rate.

The reagent ratio was set at two parts fuel oil to one part frother, and was maintained at this level throughout the program. The reagents were emulsified prior to the start of each test to enable higher flow rates through the reagent pump, thereby facilitating accurate monitoring of reagent addition. The tests were conducted as a series of four major test runs, using a fixed flow rate for each test run. A minimum of 1200 seconds (20 minutes) was allowed between test points to ensure steady-state operation. Product and tailings samples were collected simultaneously. The feed coal was sampled whenever the coal sample barrel was switched. The bench-scale tests conditions are shown in Table 31, and results are shown in Table 32. In general, it can be seen that all tests, except one, achieved the ash target of 5.0% and at least half of them also provided energy recoveries higher than 85%. The scaleable parameters for these tests are shown in Table 33.

As can be seen from the data for tests B-8-1 through B-8-5, the packed column was operated at high mass loadings with a feed of 3.34 tph/m^2 (5.4 gm/min/cm^2) and froth at 2.4 tph/m^2 (4.0 gm/min/cm^2), and still achieved good process efficiency. The results in Table 32 for these tests show that a high energy recovery of 87% was achieved at a product ash content of 4.9%. These data compare quite favorably with those of tests B-6 through B-10 where the mass loading is 33% lower and the energy recoveries are only marginally higher.

The drop in recovery as the feed rate is increased cannot be directly accounted for by the test work. This drop could either be related to the corresponding reduction in slurry residence time (bubble attachment) or may be the result of froth dropback as the froth mass flow increases. However, over the test range considered, the maximum froth loading was not determined and the possibility exists of higher loadings than 2.4 tph/m^2 (4.0 gm/min/cm^2), used in Test B-8-3, may be improved further without sacrificing either recovery or quality.

Table 31. Bench-Scale Test Conditions for Packed Column

Test Number	Feed Flow Rate l/min	Feed Flow Rate $m^3/s \times 10^{-3}$	Solids %	Mass Feed Rate gm/min	Mass Feed Rate Kg/s	Fuel Oil lb/ton	Fuel Oil Kg/t	Frother lb/ton	Frother Kg/t	Froth Depth in	Froth Depth m	Wash Water gpm	Wash Water $m^3/s \times 10^{-3}$	Air cfm	Air $m^3/s \times 10^{-3}$
7.6 cm (3 inch) diameter x 366 cm (12 ft.) tall															
A-1	2.71	0.045	3.00	81.30	0.0014	4.42	2.21	2.21	1.11	65	1.65	0.20	0.013	0.50	0.236
A-2	2.71	0.045	3.00	81.30	0.0014	4.42	2.21	2.21	1.11	87	2.21	0.20	0.013	0.50	0.236
A-3	2.71	0.045	3.00	81.30	0.0014	2.00	1.00	1.00	0.50	89	2.26	0.20	0.013	0.50	0.236
A-3A	2.71	0.045	3.00	81.30	0.0014	2.00	1.00	1.00	0.50	92	2.34	0.20	0.013	0.50	0.236
A-4	2.71	0.045	3.00	81.30	0.0014	2.00	1.00	1.00	0.50	71	1.80	0.20	0.013	0.50	0.236
A-5	2.71	0.045	3.00	81.30	0.0014	2.00	1.00	1.00	0.50	62	1.57	0.20	0.013	1.00	0.472
A-6	2.71	0.045	3.00	81.30	0.0014	2.00	1.00	0.75	0.38	84	2.13	0.20	0.013	0.45	0.212
A-7	2.71	0.045	3.00	81.30	0.0014	1.50	0.75	0.75	0.38	31	0.79	0.20	0.013	0.45	0.212
A-8	2.71	0.045	3.00	81.30	0.0014	1.50	0.75	0.75	0.38	70	1.78	0.20	0.013	0.55	0.260
A-9	2.71	0.045	3.00	81.30	0.0014	1.50	0.75	1.40	0.70	36	0.91	0.30	0.019	0.50	0.236
A-10	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	32	0.81	0.30	0.019	0.50	0.236
A-11	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	33	0.84	0.20	0.013	0.50	0.236
A-12	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	45	1.14	0.00	0.000	0.50	0.236
A-13	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	84	2.13	0.00	0.000	0.60	0.283
B-1	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	48	1.22	0.30	0.019	0.55	0.260
B-2	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	42	1.07	0.30	0.019	0.80	0.378
B-3	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	27	0.69	0.20	0.013	0.80	0.378
B-4	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	14	0.36	0.20	0.013	0.60	0.283
B-5	2.71	0.045	3.00	81.30	0.0014	2.80	1.40	1.40	0.70	33	0.84	0.20	0.013	0.50	0.236
B-6	5.42	0.091	3.00	162.60	0.0027	2.80	1.40	1.40	0.70	14	0.36	0.20	0.013	0.50	0.236
B-7	5.42	0.091	3.00	162.60	0.0027	2.80	1.40	1.40	0.70	29	0.74	0.25	0.016	0.50	0.236
B-8	5.42	0.091	3.00	162.60	0.0027	2.80	1.40	1.40	0.70	54	1.37	0.20	0.013	0.50	0.236
B-9	5.42	0.091	3.00	162.60	0.0027	2.80	1.40	1.40	0.70	70	1.78	0.25	0.016	0.50	0.236
B-10	5.42	0.091	3.00	162.60	0.0027	2.80	1.40	1.40	0.70	66	1.68	0.20	0.013	0.50	0.236
B-8-1	8.20	0.137	3.00	246.00	0.0041	1.85	0.93	0.92	0.46	15	0.38	0.20	0.013	0.55	0.260
B-8-2	8.20	0.137	3.00	246.00	0.0041	1.85	0.93	0.92	0.46	68	1.73	0.20	0.013	0.40	0.189
B-8-3	8.20	0.137	3.00	246.00	0.0041	1.85	0.93	0.92	0.46	24	0.61	0.20	0.013	0.40	0.189
B-8-4	8.20	0.137	3.00	246.00	0.0041	1.85	0.93	0.92	0.46	55	1.40	0.20	0.013	0.40	0.189
B-8-5	8.20	0.137	3.00	246.00	0.0041	1.85	0.93	0.92	0.46	75	1.91	0.20	0.013	0.40	0.189

Table 32. Bench-Scale Test Results for Packed Column

	Feed		Product		Tailings		Analysis			
Test Number	Ash %	Sulfur %	Ash %	Sulfur %	Ash %	Sulfur %	Yield %	CMR %	Ash Rej %	TSR %
7.6 cm (3 inch) diameter x 366 cm (12 ft.) tall										
A-1	20.6	1.12	3.2	1.00	64.3	1.34	72	87	89	36
A-2	20.6	1.12	3.1	0.99	63.5	1.41	71	87	89	37
A-3	20.2	1.12	1.8	0.95	23.2	1.16	14	17	99	88
A-3A	20.2	1.12	4.1	1.03	63.1	1.34	73	87	85	33
A-4	20.2	1.12	2.5	0.98	39.9	1.30	53	64	94	54
A-5	20.2	1.12	4.0	0.99	63.9	1.39	73	88	86	36
A-6	21.0	1.10	4.4	1.03	56.6	1.27	68	83	86	36
A-7	21.0	1.10	2.9	0.99	46.2	1.27	58	72	92	48
A-8	21.0	1.10	2.7	0.98	40.2	1.22	51	63	94	54
A-9	20.6	1.11	3.8	1.02	65.8	1.26	73	88	87	33
A-10	20.6	1.11	3.9	1.03	65.3	1.33	73	88	86	32
A-11	20.6	1.11	4.0	1.03	66.3	1.28	73	89	86	32
A-12	20.6	1.11	4.9	1.03	67.4	1.28	75	90	82	31
A-13	20.6	1.11	4.6	1.01	70.1	1.37	75	91	83	31
B-1	20.0	1.12	3.5	1.02	62.8	1.34	72	87	87	34
B-2	20.0	1.12	3.9	1.04	66.5	1.33	74	89	86	31
B-3	20.0	1.12	3.7	1.03	69.1	1.32	75	90	86	31
B-4	20.0	1.12	4.9	1.07	70.4	1.30	77	91	81	27
B-5	20.0	1.12	4.1	1.04	63.6	1.35	73	88	85	32
B-6	19.6	1.10	5.2	1.04	62.2	1.26	75	88	80	29
B-7	19.6	1.10	4.3	1.02	58.8	1.24	72	86	84	33
B-8	19.6	1.10	3.8	1.01	54.9	1.30	69	83	86	36
B-9	19.6	1.10	3.1	0.99	40.5	1.27	56	67	91	50
B-10	19.6	1.10	3.4	0.99	55.1	1.36	69	83	88	38
B-8-1	19.0	1.13	4.1	1.02	49.5	1.35	67	79	86	39
B-8-2	19.0	1.13	3.1	0.98	45.2	1.31	62	74	90	46
B-8-3	19.0	1.13	4.9	1.04	59.8	1.38	74	87	81	32
B-8-4	19.0	1.13	3.5	1.01	51.4	1.40	68	81	88	40
B-8-5	19.0	1.13	2.8	0.98	22.0	1.16	15	19	98	87

Table 33. Packed Column: Superficial Velocities and Mass Loadings (Raw Coal)

			Superficial Velocities						Mass Loadings			
	Mean Residence Time		Feed		Wash Water		Air		Feed		Froth	
Test Number	min	s	cm/s	m/s	cm/s	m/s	cm/s	m/s	gm/min/ cm^2	tph/ m^2	gm/min/ cm^2	tph/ m^2
7.6 cm (3 inch) diameter x 366 cm (12 ft.) tall												
A-1	3.37	202.50	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	1.28	0.77
A-2	2.44	146.11	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	1.27	0.76
A-3	2.35	140.98	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	0.25	0.15
A-3A	2.22	133.29	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	1.30	0.78
A-4	3.12	187.12	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	0.94	0.56
A-5	3.50	210.19	0.99	0.0099	0.28	0.0028	10.36	0.1036	1.78	1.07	1.30	0.78
A-6	2.56	153.80	0.99	0.0099	0.28	0.0028	4.66	0.0466	1.78	1.07	1.22	0.73
A-7	4.83	289.65	0.99	0.0099	0.28	0.0028	4.66	0.0466	1.78	1.07	1.04	0.62
A-8	3.16	189.68	0.99	0.0099	0.28	0.0028	5.70	0.0570	1.78	1.07	0.91	0.55
A-9	4.61	276.83	0.99	0.0099	0.42	0.0042	5.18	0.0518	1.78	1.07	1.30	0.78
A-10	4.78	287.09	0.99	0.0099	0.42	0.0042	5.18	0.0518	1.78	1.07	1.30	0.78
A-11	4.74	284.52	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	1.31	0.78
A-12	4.23	253.76	0.99	0.0099	0.00	0.0000	5.18	0.0518	1.78	1.07	1.33	0.80
A-13	2.56	153.80	0.99	0.0099	0.00	0.0000	6.21	0.0621	1.78	1.07	1.35	0.81
B-1	4.10	246.07	0.99	0.0099	0.42	0.0042	5.70	0.0570	1.78	1.07	1.29	0.77
B-2	4.36	261.45	0.99	0.0099	0.42	0.0042	8.28	0.0828	1.78	1.07	1.32	0.79
B-3	5.00	299.90	0.99	0.0099	0.28	0.0028	8.28	0.0828	1.78	1.07	1.34	0.80
B-4	5.55	333.23	0.99	0.0099	0.28	0.0028	6.21	0.0621	1.78	1.07	1.37	0.82
B-5	4.74	284.52	0.99	0.0099	0.28	0.0028	5.18	0.0518	1.78	1.07	1.31	0.78
B-6	2.78	166.61	1.98	0.0198	0.28	0.0028	5.18	0.0518	3.57	2.14	2.67	1.60
B-7	2.46	147.39	1.98	0.0198	0.35	0.0035	5.18	0.0518	3.57	2.14	2.57	1.54
B-8	1.92	115.35	1.98	0.0198	0.28	0.0028	5.18	0.0518	3.57	2.14	2.47	1.48
B-9	1.58	94.84	1.98	0.0198	0.35	0.0035	5.18	0.0518	3.57	2.14	2.00	1.20
B-10	1.67	99.97	1.98	0.0198	0.28	0.0028	5.18	0.0518	3.57	2.14	2.45	1.47
B-8-1	1.82	109.28	3.00	0.0300	0.28	0.0028	5.70	0.0570	5.40	3.24	3.62	2.17
B-8-2	1.07	64.38	3.00	0.0300	0.28	0.0028	4.14	0.0414	5.40	3.24	3.35	2.01
B-8-3	1.69	101.66	3.00	0.0300	0.28	0.0028	4.14	0.0414	5.40	3.24	4.01	2.40
B-8-4	1.26	75.39	3.00	0.0300	0.28	0.0028	4.14	0.0414	5.40	3.24	3.65	2.19
B-8-5	0.97	58.45	3.00	0.0300	0.28	0.0028	4.14	0.0414	5.40	3.24	0.83	0.50

Figure 11 illustrates the major trends observed in the raw coal tests in the packed column in terms of the relationship between energy recovery and ash content of the product coal. Along similar lines, Figure 12 illustrates the performance of the cell in terms of the sulfur content of the product coal. The relationship of energy recovery to ash and sulfur rejection is also shown in Figure 13 and Figure 14. As can be seen in Figure 14, total sulfur rejections of about 35% can be obtained at energy recoveries of 85%.

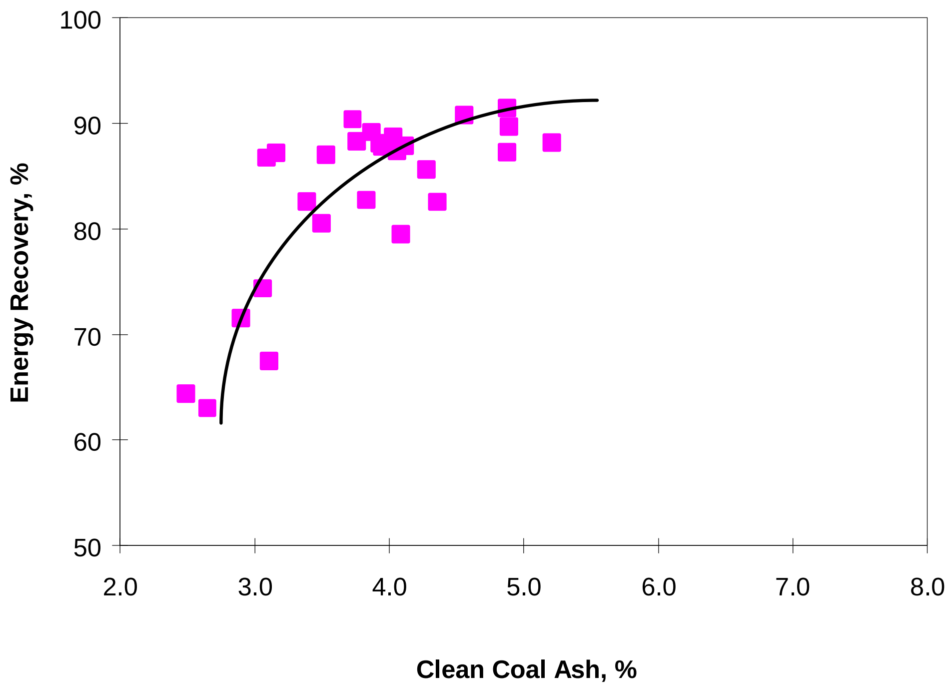

Figure 11. Packed Column: Energy Recovery vs. Clean Coal Ash

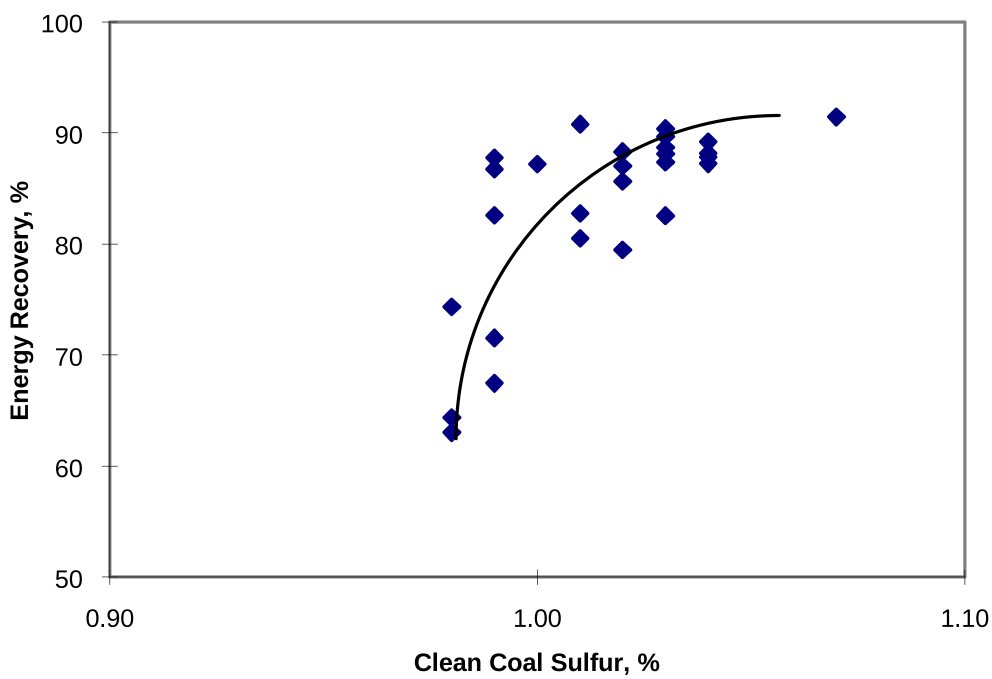

Figure 12. Packed Column: Energy Recovery vs. Clean Coal Sulfur

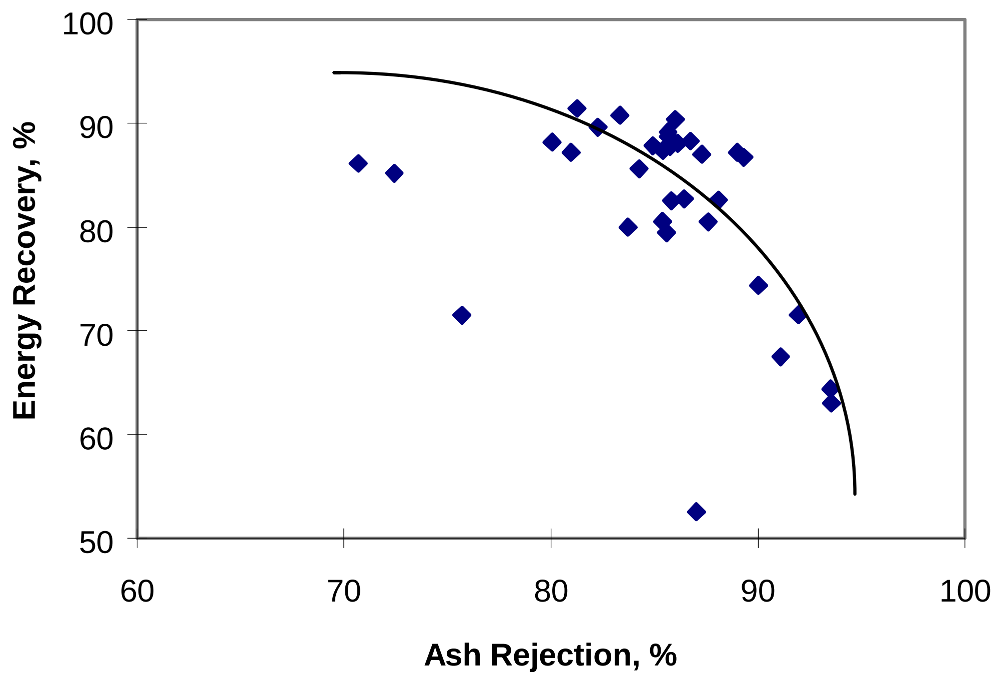

Figure 13. Packed Column: Energy Recovery vs. Ash Rejection

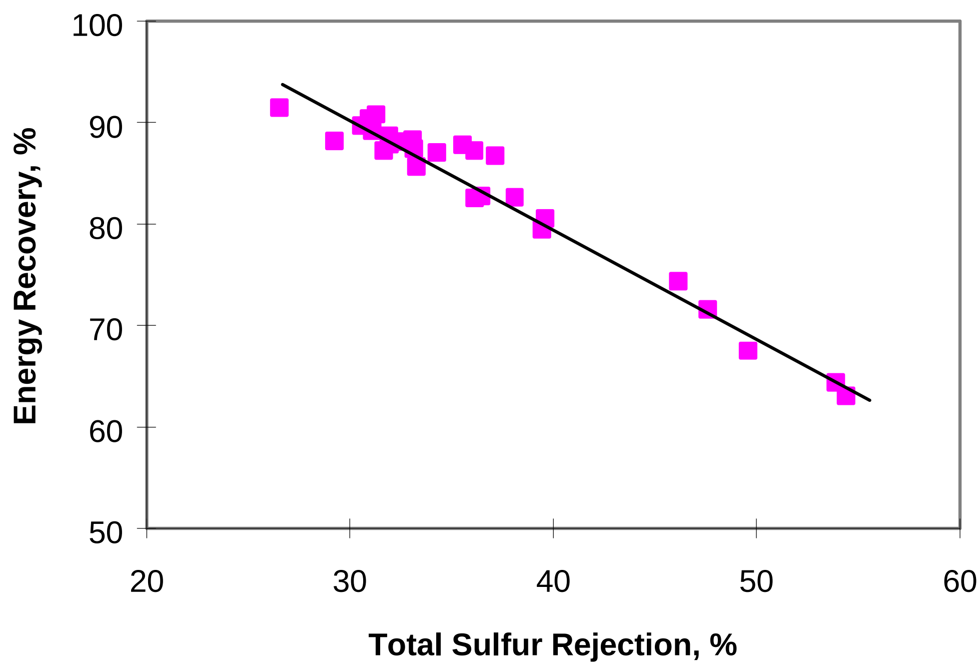

Figure 14. Packed Column: Energy Recovery vs. Sulfur Rejection

5.4.2 Second-Stage Test Work

Tests were conducted on a tailings sample at 1.4% solids, again using the 12-ft tall column. The conditions and results are included in Table 34 and Table 35. The operating conditions reduced to standard scaleable parameters such as superficial velocities, mass loading, and residence times are shown in Table 36. The tests were run at a feed velocity of 3 cm/s, which corresponds to a 2-minute residence time, and achieved froth loadings of up to 0.68 tph/m^2. Table 36 presents the analysis of the test results. At these conditions, the tailings ash was about 75% and energy recovery was 74-76%. The clean coal ash content ranged between 6.5 and 10%, indicating good separation efficiency for second-stage operations.

Figure 15 and Figure 16 illustrate the overall performance of this cell in terms of the relationship between energy recovery and clean coal ash, and energy recovery and product sulfur respectively. Figure 17 and Figure 18 depict the relationship between energy recovery and ash rejection and sulfur rejection, respectively.

Table 34. Packed Column Test Conditions for Tailings Sample

Test	Feed Rate		Solids	Feed Rate		Fuel Oil		Frother		Froth Depth		Wash Water		Air	
Number	l/min	m^3/s x 10^{-3}	%	gm/ min	Kg/ s	lb/ ton	Kg/ t	lb/ ton	Kg/ t	in	m	gpm	m^3/s x 10^{-3}	cfm	m^3/s x 10^{-3}
T-1	8.11	0.135	1.40	113.54	0.0019	2.80	1.40	1.40	0.70	5	0.13	0.20	0.013	0.40	0.189
T-2	8.11	0.135	1.40	113.54	0.0019	2.80	1.40	1.40	0.70	5	0.13	0.20	0.013	0.40	0.189
T-3	8.11	0.135	1.40	113.54	0.0019	2.80	1.40	1.40	0.70	5	0.13	0.20	0.013	0.40	0.189
T-4	8.11	0.135	1.40	113.54	0.0019	2.80	1.40	1.40	0.70	12	0.30	0.20	0.013	0.40	0.189

Table 35. Packed Column Test Results for Tailings Sample

Test	Feed			Product			Tailings			Analysis				
	Ash	Sulfur	Pyr. S	Ash	Sulfur	Pyr. S	Ash	Sulfur	Pyr. S	Yield	CMR	Ash Rej	TSR	PSR
Number	%	%	%	%	%	%	%	%	%	%	%	%	%	%
T-1	46.1	2.10		7.0	1.98		75.3	2.17		43	74	94	60	0
T-2	46.1	2.10		10.4	2.25		75.5	2.01		45	75	90	52	0
T-3	46.1	2.10	1.67	6.5	1.88	0.80	75.5	2.14	1.80	43	74	94	62	80
T-4	46.1	2.10		9.3	2.12		76.7	2.12		45	76	91	54	0

Table 36. Packed Column: Superficial Velocities and Mass Loadings

			Superficial Velocities						Mass Loadings			
	Mean Residence Time		Feed		Wash Water		Air		Feed		Froth	
Test Number	min	s	cm/s	m/s	cm/s	m/s	cm/s	m/s	gm/min/ cm^2	tph/ m^2	gm/min/ cm^2	tph/ m^2
T-1	1.98	119.06	2.97	0.0297	0.28	0.0028	4.14	0.0414	2.49	1.49	1.06	0.64
T-2	1.98	119.06	2.97	0.0297	0.28	0.0028	4.14	0.0414	2.49	1.49	1.12	0.67
T-3	1.98	119.06	2.97	0.0297	0.28	0.0028	4.14	0.0414	2.49	1.49	1.06	0.64
T-4	1.88	113.06	2.97	0.0297	0.28	0.0028	4.14	0.0414	2.49	1.49	1.13	0.68

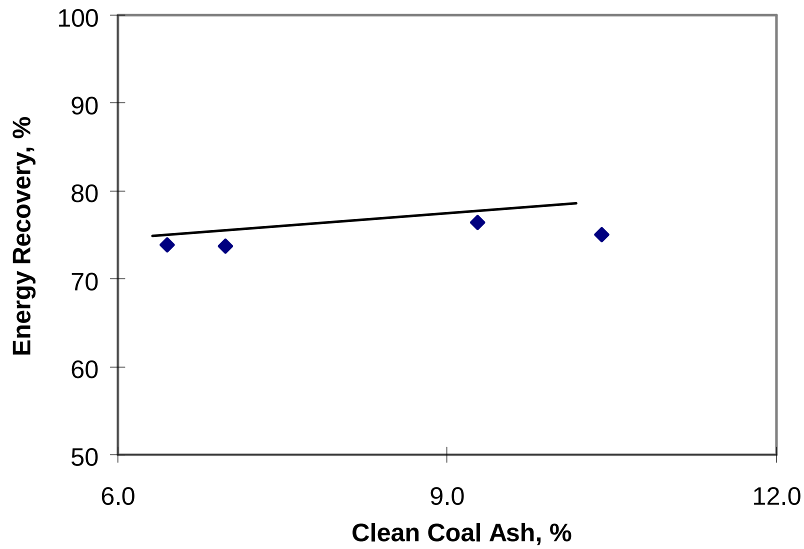

Figure 15. Packed Column: Energy Recovery vs. Product Ash (Tailings Sample)

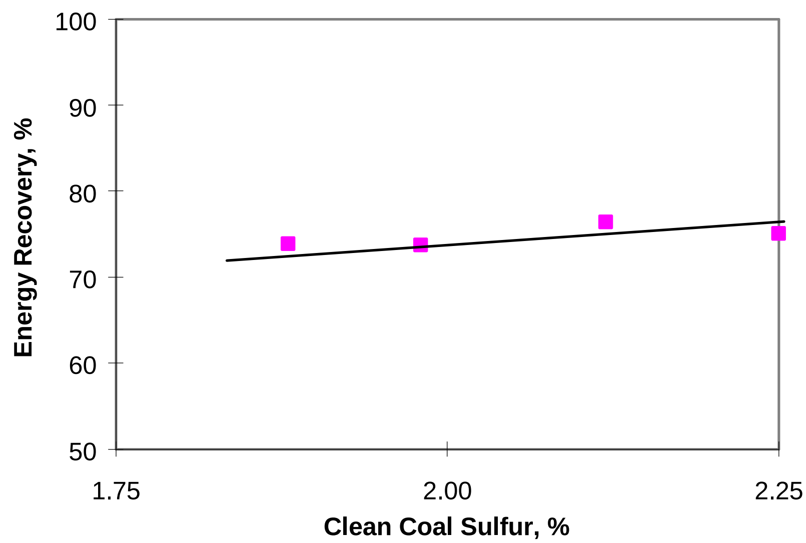

Figure 16. Packed Column: Energy Recovery vs. Clean Coal Sulfur (Tailings Sample)

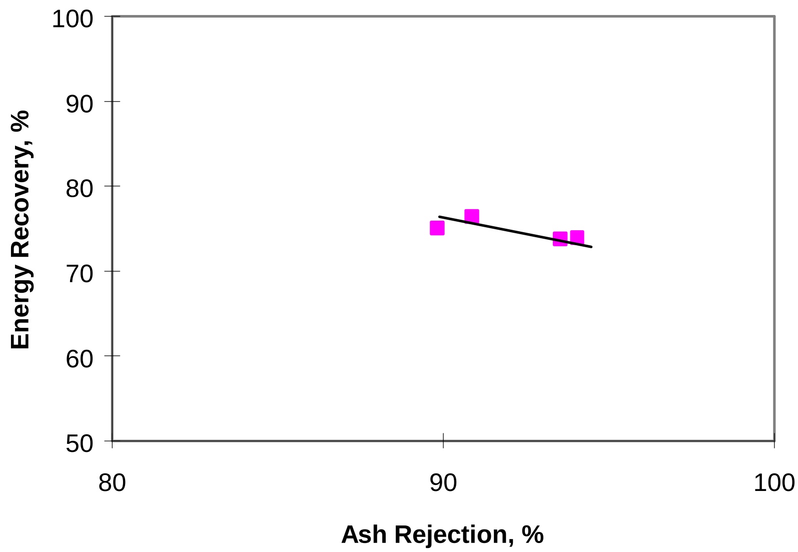

Figure 17. Packed Column: Energy Recovery vs. Ash Rejection (Tailings Sample)

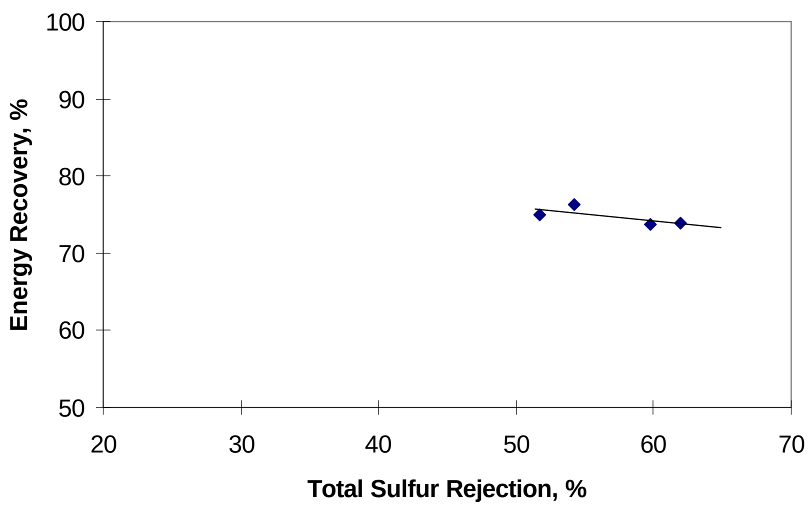

Figure 18. Packed Column: Energy Recovery vs. Sulfur Rejection (Tailings Sample)

5.4.3 Recommended Operating Conditions

The recommended conditions for packed column operation are given in Table 37 for single-stage operation and Table 38 for its use as a second-stage unit.

Table 37. Packed Column: Recommended Single-Stage Operating Conditions

Parameter	*Value*
Feed flow rate	3 cm/s (6 ft/min)
Residence time	150 seconds (2.5 min)
Froth depth	35.5 cm (14 inch) minimum
Fuel oil	1.0 kg/t (2 lb/ton)
Frother	0.6 kg/t (1.4 lb/ton) or 10 ppm
Aeration rate	4-5 cm/s (8-10 ft/min)
Wash water flow rate	0.15 cm/s (0.3 ft/min)

Table 38. Packed Column: Recommended Second-Stage Operating Conditions(1)

Parameter	*Value*
Feed flow rate	2-3 cm/s (4-6 ft/min)
Residence time	120-180 seconds (2-3 min)
Froth depth	25 cm (12 inch) minimum
Fuel oil	1.0 kg/t (2 lb/ton)
Frother	0.5 kg/t (1 lb/ton)
Aeration rate	6 cm/s (12 ft/min)
Wash water flow rate	0.28 cm/s (0.6 ft/min)

(1) Assumes 1.4% solids in feed

5.5 Open Column

A 2.5-in. diameter x 18-ft tall column was used for these tests. A total of 27 tests were conducted on the raw coal sample to determine the effects of the major operating variables. The test conditions for these tests are given in Table 39 and their results are given in Table 40. The scaleable parameters are given in Table 41.

The breakdown of these tests is as follows:

- Tests 1-9 were conducted to determine the reagent dosages.
- Tests 10-20 were conducted to determine the effects of feed rate, wash water addition, and aeration rates.
- Tests 21-23 were conducted to determine the effects of residence time.
- Tests 24-27 were conducted to determine the effects of high volumetric flow rates.

In all cases, the test procedure consisted of the following steps. A large batch of feed slurry was agitated and the solids content measured. Fuel oil was then added to the batch to achieve the desired reagent dosage prior to the start of the testing. A stirred 5-gallon tank was continuously fed slurry from this large batch. Frother was added to the stirred 5-gallon tank at a rate proportional to the column feed flow rate as a means of conditioning the coal before injecting it into the column. This approach was used to ensure that the frother maintained the same contact time with the coal for all tests. Frother solution equivalent to 10 ppm was also added into the air sparger water and used as wash water to ensure proper bubble size.

A minimum of 20 minutes was allowed between test points to achieve steady-state operation. Product and tailings samples were collected simultaneously. The mass flows of product and tailings were measured and used to reconstruct the feed coal quality. The results of the tests are discussed in the following sections.

Table 39. Bench-Scale Test Conditions for Open Column (Raw Coal)

	Feed Flow Rate		Solids	Mass Flow Rate		Fuel Oil		Frother		Froth Depth		Wash Water		Air	
Test Number	ml/min	$m^3/s \times 10^{-3}$	%	gm/ min	Kg/ s	lb/ ton	Kg/ t	lb/ ton	Kg/ t	in	m	ml/min	m^3/s	l/min	m^3/s $\times 10^{-3}$
1	1500	0.03	6.00	93.86	0.0016	1.00	0.50	0.59	0.30	40	1.02	380	6.35	3.00	0.050
2	1500	0.03	6.00	93.86	0.0016	1.00	0.50	0.59	0.30	40	1.02	380	6.35	3.00	0.050
4	1500	0.03	2.60	39.72	0.0007	1.00	0.50	0.50	0.25	24	0.61	380	6.35	3.00	0.050
5	1500	0.03	2.60	39.72	0.0007	1.75	0.88	0.50	0.25	24	0.61	380	6.35	3.00	0.050
6	1500	0.03	2.60	39.72	0.0007	2.00	1.00	0.50	0.25	24	0.61	380	6.35	3.00	0.050
7	1500	0.03	2.60	39.72	0.0007	2.00	1.00	1.14	0.57	24	0.61	380	6.35	3.00	0.050
8	1500	0.03	2.60	39.72	0.0007	1.75	0.88	1.14	0.57	24	0.61	380	6.35	3.00	0.050
9	1500	0.03	2.60	39.72	0.0007	1.25	0.63	1.14	0.57	24	0.61	380	6.35	3.00	0.050
10	1500	0.03	6.70	102.64	0.0017	1.04	0.52	0.41	0.21	30	0.76	570	9.52	4.20	0.070
11	1530	0.03	4.63	71.85	0.0012	1.04	0.52	0.59	0.30	30	0.76	570	9.52	1.90	0.032
12	1521	0.03	4.36	67.12	0.0011	1.04	0.52	0.52	0.26	30	0.76	190	3.17	4.18	0.070
13	1521	0.03	1.91	29.22	0.0005	1.04	0.52	1.20	0.60	30	0.76	190	3.17	1.90	0.032
14	2450	0.04	3.57	88.31	0.0015	1.04	0.52	0.53	0.27	30	0.76	380	6.35	3.04	0.051
15	2450	0.04	4.10	101.61	0.0017	1.04	0.52	0.46	0.23	30	0.76	380	6.35	3.04	0.051
16	3421	0.06	2.39	82.37	0.0014	1.04	0.52	0.62	0.31	30	0.76	190	3.17	1.90	0.032
17	3421	0.06	2.04	70.25	0.0012	1.04	0.52	0.73	0.37	30	0.76	190	3.17	4.18	0.070
18	3421	0.06	1.68	57.74	0.0010	1.04	0.52	1.02	0.51	30	0.76	570	9.52	4.18	0.070
19	3421	0.06	1.73	59.59	0.0010	1.04	0.52	0.99	0.50	30	0.76	570	9.52	1.90	0.032
20	2471	0.04	1.20	29.67	0.0005	1.04	0.52	1.58	0.79	30	0.76	380	6.35	3.04	0.051
21	1800	0.03	2.44	44.22	0.0007	2.00	1.00	1.11	0.55	30	0.76	380	6.35	4.50	0.075
22	1800	0.03	2.69	48.76	0.0008	2.00	1.00	1.00	0.50	30	0.76	380	6.35	4.50	0.075
23	1800	0.03	3.43	62.42	0.0010	2.00	1.00	0.79	0.39	30	0.76	380	6.35	4.50	0.075
24	3000	0.05	1.24	37.40	0.0006	2.00	1.00	1.53	0.76	30	0.76	380	6.35	4.20	0.070
25	5000	0.08	1.48	74.20	0.0012	2.00	1.00	1.05	0.53	30	0.76	380	6.35	4.20	0.070
26	7000	0.12	1.35	95.00	0.0016	2.00	1.00	1.05	0.52	30	0.76	380	6.35	4.20	0.070
27	8560	0.14	1.12	96.60	0.0016	2.00	1.00	1.25	0.62	30	0.76	380	6.35	4.20	0.070

Table 40. Bench-Scale Test Results for Open Column (Raw Coal)

	Feed			Product			Tailings			Analysis			
Test Number	Ash %	Sulfur %	Pyr. S. %	Ash %	Sulfur %	Pyr. S. %	Ash %	Sulfur %	Pyr. S. %	Yield, %	CMR, %	Ash Rej %	TSR %
1	20.4			2.0			29.8			34	42	97	
2	21.4			3.9			30.8			35	43	94	
4	21.0			3.1			31.8			38	46	95	
5	19.8			3.8			36.3			51	61	90	
6	19.7			3.8			36.1			51	61	90	
7	19.5			4.1			59.3			72	86	85	
8	18.9			3.8			50.3			68	80	86	
9	20.2			3.6			48.4			63	76	89	
10	20.2	1.05		3.1	0.94		25.2	1.06		22	27	97	80
11	20.6	1.05		2.9	0.94		23.7	1.29		15	18	98	87
12	21.3	1.04		3.4	1.00		25.8	0.95		20	24	97	81
13	22.0	1.07		3.5	0.92		29.2	1.09		28	35	96	76
14	20.5	1.02		3.3	1.08		25.2	1.55		21	26	97	77
15	19.6	1.01		3.2	0.92		25.0	1.00		25	30	96	77
16	21.3	1.02		3.6	0.83		21.7	1.01		2	2	100	99
17	21.3	0.97		4.4	0.92		50.3	1.37		63	77	87	40
18	21.6	0.98		3.6	0.93		50.4	1.26		62	76	90	44
19	21.3	1.07		3.8	0.97		37.6	1.12		48	59	91	56
20	21.5	1.04	0.49	4.0	0.94	0.24	59.3	1.19	1.01	68	84	87	38
21	19.5	1.06		8.2	0.97		83.4	1.18		85	97	64	22
22	19.1	1.01		5.3	0.99		80.9	1.13		82	96	77	20
23	19.7	1.06	0.47	5.3	1.00	0.26	74.3	1.35	1.46	79	93	79	25
24	19.1			4.2			50.5			68	80	85	
25	19.9			3.8			51.5			66	80	87	
26	18.5			3.6			46.7			65	77	87	
27	18.6			4.2			53.8			71	84	84	

measured feed ashes

Table 41. Open Column: Superficial Velocities and Mass Loadings (Raw Coal)

			Superficial Velocities						Mass Loadings			
	Mean Residence Time		Feed		Wash Water		Air		Feed		Froth	
Test Number	min	s	cm/s	m/s	cm/s	m/s	cm/s	m/s	gm/min/ cm^2	tph/ m^2	gm/min/ cm^2	tph/ m^2
1	9.43	566.01	0.79	0.0079	0.20	0.0020	1.58	0.0158	2.97	1.78	1.01	0.60
2	9.43	566.01	0.79	0.0079	0.20	0.0020	1.58	0.0158	2.97	1.78	1.04	0.62
4	10.29	617.46	0.79	0.0079	0.20	0.0020	1.58	0.0158	1.25	0.75	0.47	0.28
5	10.29	617.46	0.79	0.0079	0.20	0.0020	1.58	0.0158	1.25	0.75	0.64	0.38
6	10.29	617.46	0.79	0.0079	0.20	0.0020	1.58	0.0158	1.25	0.75	0.64	0.38
7	10.29	617.46	0.79	0.0079	0.20	0.0020	1.58	0.0158	1.25	0.75	0.91	0.54
8	10.29	617.46	0.79	0.0079	0.20	0.0020	1.58	0.0158	1.25	0.75	0.85	0.51
9	10.29	617.46	0.79	0.0079	0.20	0.0020	1.58	0.0158	1.25	0.75	0.79	0.47
10	9.97	598.17	0.79	0.0079	0.30	0.0030	2.21	0.0221	3.24	1.95	0.73	0.44
11	9.77	586.44	0.81	0.0081	0.30	0.0030	1.00	0.0100	2.27	1.36	0.34	0.20
12	9.83	589.91	0.80	0.0080	0.10	0.0010	2.20	0.0220	2.12	1.27	0.42	0.25
13	9.83	589.91	0.80	0.0080	0.10	0.0010	1.00	0.0100	0.92	0.55	0.26	0.15
14	6.10	366.23	1.29	0.0129	0.20	0.0020	1.60	0.0160	2.79	1.67	0.60	0.36
15	6.10	366.23	1.29	0.0129	0.20	0.0020	1.60	0.0160	3.21	1.93	0.80	0.48
16	4.37	262.28	1.80	0.0180	0.10	0.0010	1.00	0.0100	2.60	1.56	0.05	0.03
17	4.37	262.28	1.80	0.0180	0.10	0.0010	2.20	0.0220	2.22	1.33	1.40	0.84
18	4.37	262.28	1.80	0.0180	0.30	0.0030	2.20	0.0220	1.82	1.09	1.12	0.67
19	4.37	262.28	1.80	0.0180	0.30	0.0030	1.00	0.0100	1.88	1.13	0.91	0.55
20	6.05	363.11	1.30	0.0130	0.20	0.0020	1.60	0.0160	0.94	0.56	0.64	0.39
21	8.31	498.47	0.95	0.0095	0.20	0.0020	2.37	0.0237	1.40	0.84	1.19	0.71
22	5.09	305.52	0.95	0.0095	0.20	0.0020	2.37	0.0237	1.54	0.92	1.26	0.76
23	1.88	112.56	0.95	0.0095	0.20	0.0020	2.37	0.0237	1.97	1.18	1.56	0.94
24	4.98	299.08	1.58	0.0158	0.20	0.0020	2.21	0.0221	1.18	0.71	0.80	0.48
25	2.99	179.45	2.63	0.0263	0.20	0.0020	2.21	0.0221	2.34	1.41	1.55	0.93
26	2.14	128.18	3.69	0.0369	0.20	0.0020	2.21	0.0221	3.00	1.80	1.96	1.18
27	1.75	104.82	4.51	0.0451	0.20	0.0020	2.21	0.0221	3.05	1.83	2.17	1.30

5.5.1 Reagent Dosage Tests

During these tests, the volumetric feed rate was maintained constant, though some variations in percent solids were observed. The frother dosage was varied between 0.25 kg/ton to 0.57 kg/ton (0.5 lb/ton and 1.14 lb/ton). The results of tests 7 and 8 indicate that to achieve an acceptable performance the frother and fuel oil dosages had to be 0.5 kg/ton (1 lb/ton) and 1 kg/ton (2 lb/ton) respectively. These tests showed energy recoveries of 80% and 86% at ash contents of 3.8% and 4.1% respectively.

5.5.2 Factorial Tests

After conducting the dosage tests, a three-factor, two-level series of tests was completed using the feed rate, wash water, and aeration rate as variables (tests 10-20). The reagent dosage was set at 1 kg/t (2 lb/ton) fuel oil and 0.5 kg/t (1 lb/ton) frother for these tests. Due to an error during sampling of the feed slurry its solids content was determined to be 1.7%, and the fuel oil was added accordingly. However, the actual percent solids was 3.1%, and the amount of reagents calculated on the basis of the low feed solids turned out to be insufficient and resulted in poor recoveries and performance.

Variations in the feed solids concentration were also detected during the testing based on the measured mass flow rates of the product and tailings samples. Fluctuations in the feed solids concentration measurements were possibly the result of non-steady-state recirculation of the slurry in the large batch tank, where stratification of the solids may have occurred.

The results of the parametric tests are shown in Figure 19 as a function of feed mass loading (equivalent to feed percent solids). The results indicate that energy recovery was dependent on mass loading, with high loadings leading to low recoveries. Increasing the air flow rates improved recovery over the range tested (1, 1.6, and 2.2 cm/s). The conclusions from these tests are:

- High air flow rates are required for maximum recovery
- Wash water flow rate had little effect on product quality over the range tested (0.1 to 0.3 cm/s)
- Higher levels of fuel oil are required to increase recovery

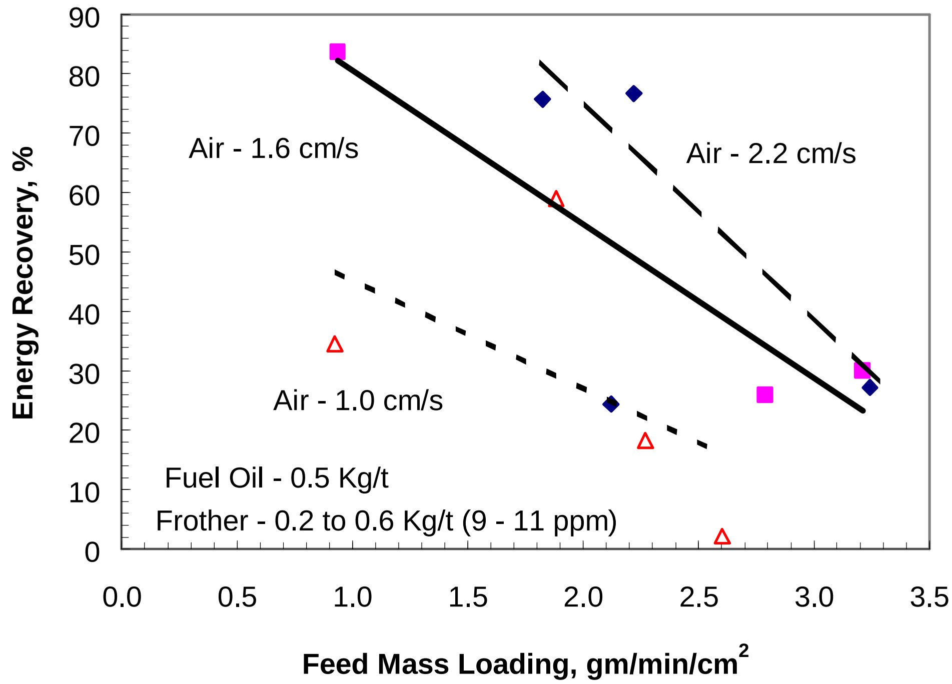

Figure 19. Open Column Parametric Test Results

5.5.3 Residence Time Tests

Prior to conducting these tests, the slurry mixing and reagent addition procedure were revised in order to ensure a more consistent performance. A constant feed rate was set for these tests and the residence time was varied by removing sections of the column. The column heights used were 5.67 m (17 ft), 3.67 (11 ft), and 1.67 (5 ft), respectively. The slurry residence time corresponding to the three column heights was 8.3, 5.1, and 1.9 minutes for tests number 21, 22, and 23, respectively in Table 39 and Table 40. The tests were run at a maximum aeration rate of 2.4 cm/s, using 1 kg/t (2 lb/ton) fuel oil and 0.5 kg/t (1 lb/ton) frother. The feed velocity was set at approximately 1 cm/sec. The higher fuel oil dosage improved operations considerably. The process efficiency was very good, and equaled that of the Jameson cell and packed column. The maximum froth loading achieved was 0.93 tph/m^2 (1.55 gm/min/cm^2). Even a residence time of 1.9 minutes (test 23) resulted in high energy recovery of 93%. The product ash for this test was 5.33%, which is somewhat higher than the target value of 5% but is consistent with the correspondingly high energy recovery and indicates that a relatively efficient separation was achieved.

5.5.4 High Volumetric Flow Rate Tests

The final series of tests was run to evaluate the effects of operating the open column at high feed velocities. Raw coal samples were diluted to 1.4% solids and were tested in the open column after reassembling it to its full height of 18 ft. The flow rates for these tests (24 through 27 in Table 39 and Table 40) ranged from 1.6 to 4.5 cm/s with corresponding residence times of 5 minutes to 1.75 minutes. Frother addition was set to a minimal level of 0.35 to 0.5 kg/t (0.7 to 1.0 lb/t) or a concentration of 6-7 ppm. The resulting performance showed that while a clean product with low ash was made, energy recoveries were not as high as in the previous tests. Were this cell to be used as a first-stage unit, this performance would be acceptable. However, as a single-stage device this performance needs to be better.

5.5.5 Summary of Raw Coal Tests

The raw coal tests results have been summarized in four graphs. Figure 20 presents the trends in clean coal ash vs. recovery. Along similar lines, the grade/recovery curve for the open column cell was determined in terms of the product sulfur content, as shown in Figure 21. Figure 22 and Figure 23 illustrate the overall performance of this cell in terms of the relationship between energy recovery and ash rejection, and energy recovery and sulfur rejection, respectively. As shown in Figure 23, total sulfur rejections of between 30 and 35% were achieved at an energy recovery of 85%.

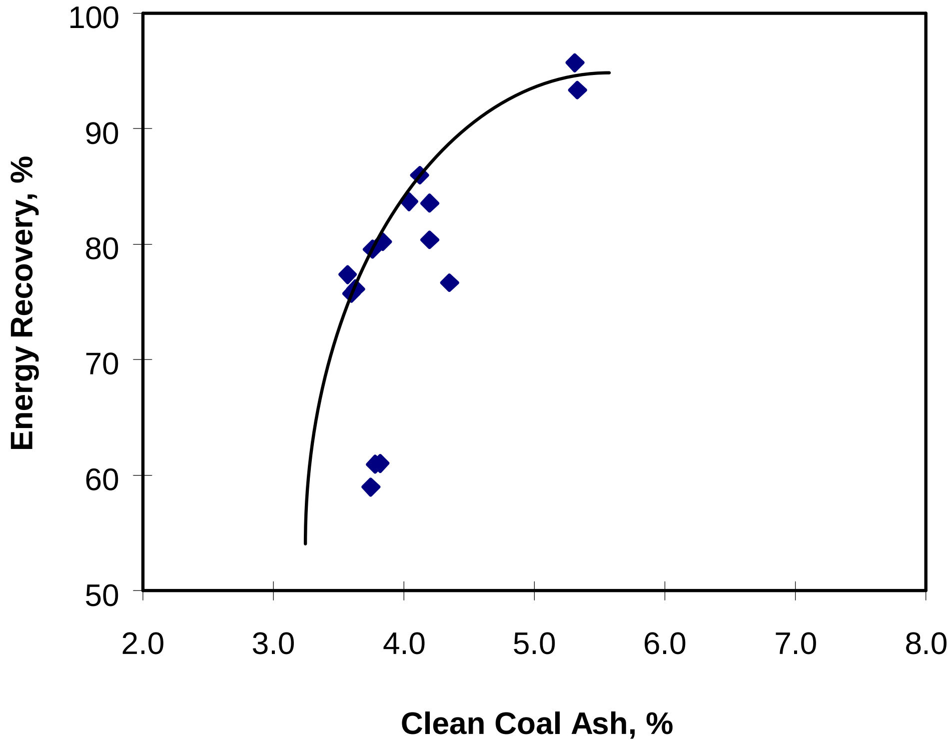

Figure 20. Open Column: Energy Recovery vs. Clean Coal Ash

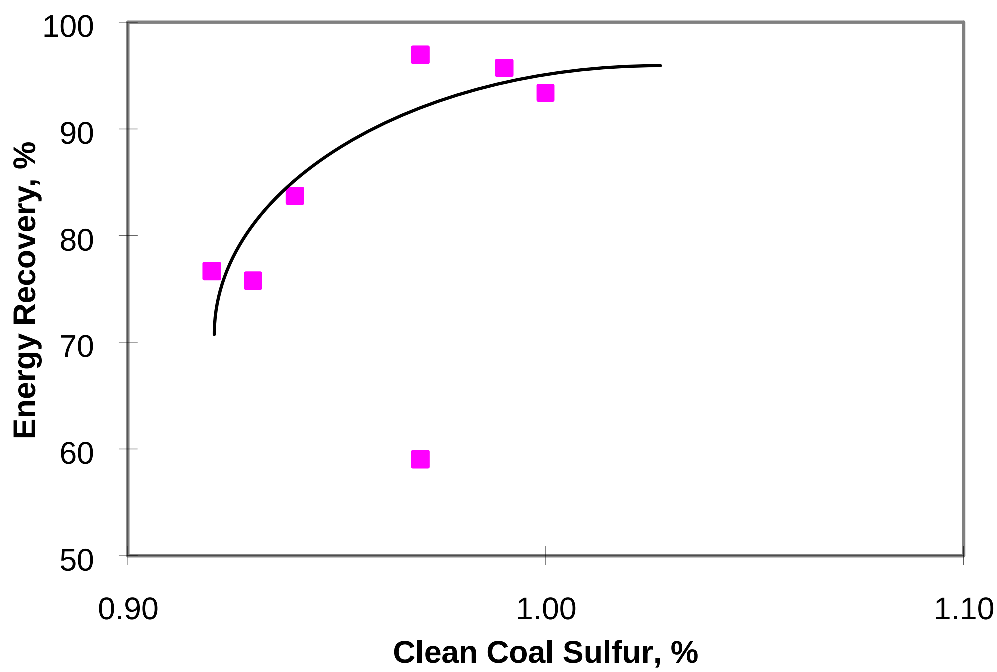

Figure 21. Open Column: Energy Recovery vs. Clean Coal Sulfur

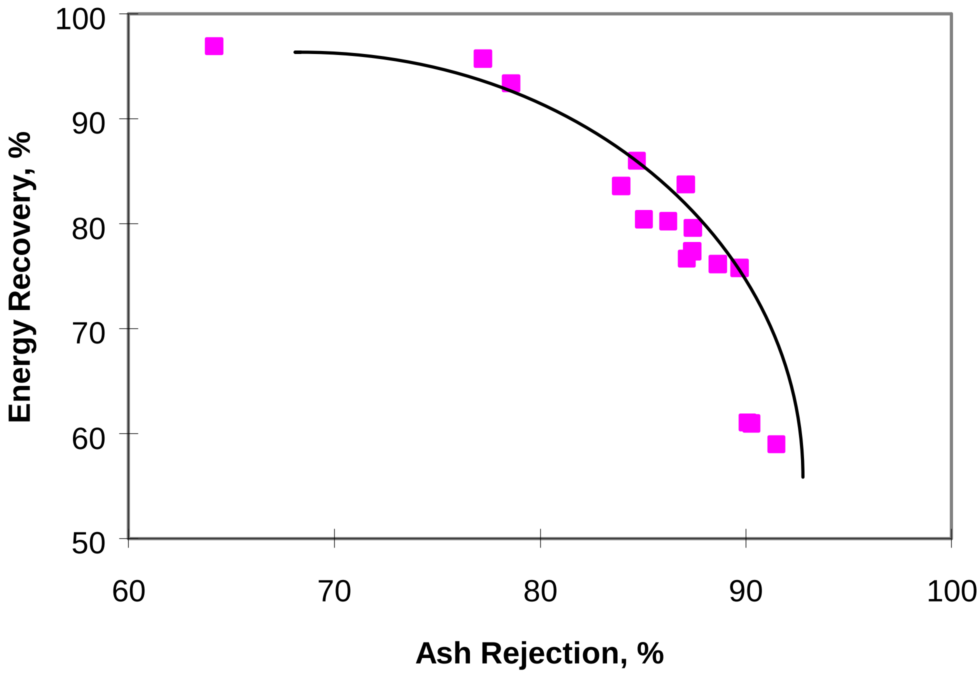

Figure 22. Open Column: Energy Recovery vs. Ash Rejection

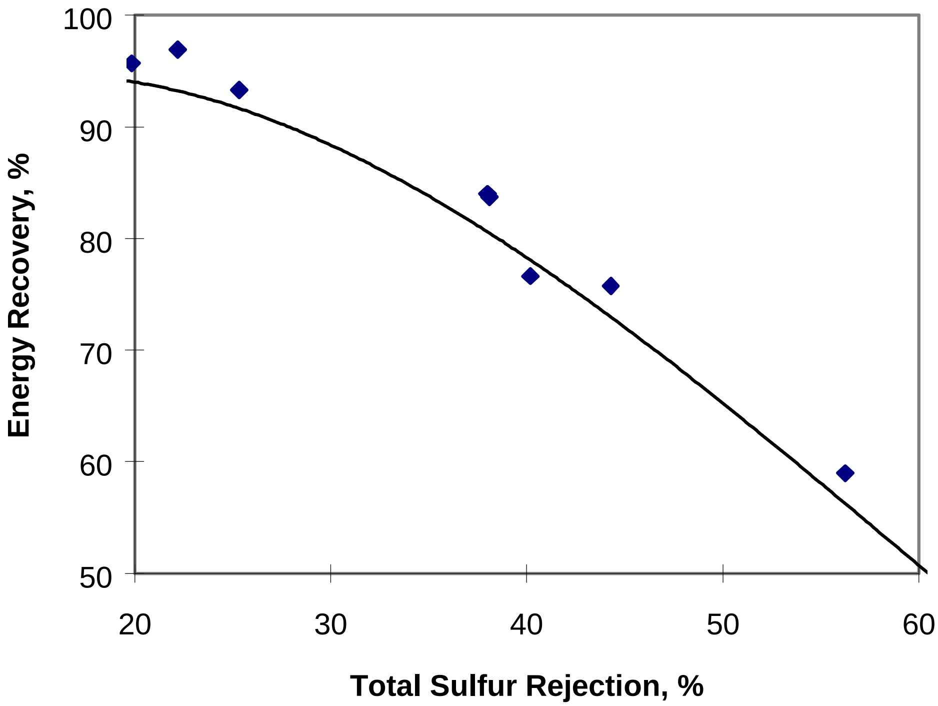

Figure 23. Open Column: Energy Recovery vs. Sulfur Rejection

5.5.6 Second-Stage Tests

Six tailings sample tests were run (tests 28-33) using three levels of feed flow rate and two levels of aeration rate. The tailings feed tests were run at a relatively high feed solids content of 2.7-3% solids. The test conditions, results, and analysis are given in Table 42 and Table 43. The scaleable parameters are shown in Table 44.

The tailings tests demonstrate that a high-ash tailings could be achieved, in the range of 80 to 85%, with good separation at feed rates of up to 1.84 cm/s.

Table 42. Open Column Test Conditions for Tailings Sample

Test Number	Feed Flow Rate ml/min	Feed Flow Rate $m^3/s \times 10^{-3}$	Solids %	Mass Flow Rate gm/min	Mass Flow Rate Kg/s	Fuel Oil lb/ton	Fuel Oil Kg/t	Frother lb/ton	Frother Kg/t	Froth Depth in	Froth Depth m	Wash Water ml/min	Wash Water m^3/s	Air l/min	Air $m^3/s \times 10^{-3}$
28	1500	0.03	2.62	39.60	0.0007	2.00	1.00	1.14	0.57	30	0.76	380	6.35	3.40	0.057
29	2500	0.04	2.59	65.20	0.0011	2.00	1.00	0.89	0.45	30	0.76	380	6.35	3.40	0.057
30	3500	0.06	2.59	91.40	0.0015	2.00	1.00	0.78	0.39	30	0.76	380	6.35	3.40	0.057
31	3500	0.06	2.59	91.40	0.0015	2.00	1.00	0.78	0.39	30	0.76	380	6.35	4.70	0.078
32	2500	0.04	2.59	65.20	0.0011	2.00	1.00	0.89	0.45	30	0.76	380	6.35	4.70	0.078
33	1500	0.03	2.61	39.40	0.0007	2.00	1.00	1.14	0.57	30	0.76	380	6.35	4.70	0.078

Table 43. Open Column Test Results for Tailings Sample

Test Number	Feed Ash %	Feed Sulfur %	Feed Pyr. S. %	Product Ash %	Product Sulfur %	Product Pyr. S. %	Tailings Ash %	Tailings Sulfur %	Tailings Pyr. S. %	Analysis Yield, %	Analysis CMR, %	Analysis Ash Rej %	Analysis TSR %
28	42.3	1.69		8.5	1.75		76.0	1.33		50	79	90	48
29	48.6	1.72		8.6	1.84		78.7	1.73		43	76	92	54
30	46.8	1.58		7.8	1.97		79.1	1.84		45	79	92	44
31	44.5	1.76	1.39	8.1	1.94	1.06	85.8	1.49	1.49	53	88	90	41
32	44.5	1.58		9.5	1.99		87.1	1.56		55	89	88	31
33	45.7	1.30		9.0	1.82		86.0	1.20		52	88	90	27

Table 44. Open Column: Superficial Velocities and Mass Loadings (Tailings Sample)

Test Number	Mean Residence Time min	Mean Residence Time s	Superficial Velocities Feed cm/s	Superficial Velocities Feed m/s	Superficial Velocities Wash Water cm/s	Superficial Velocities Wash Water m/s	Superficial Velocities Air cm/s	Superficial Velocities Air m/s	Mass Loadings Feed gm/min/cm²	Mass Loadings Feed tph/m²	Mass Loadings Froth gm/min/cm²	Mass Loadings Froth tph/m²
28	9.97	598.17	0.79	0.0079	0.20	0.0020	1.790	0.0179	1.25	0.75	0.63	0.38
29	5.98	358.90	1.32	0.0132	0.20	0.0020	1.790	0.0179	2.06	1.24	0.88	0.53
30	4.27	256.36	1.84	0.0184	0.20	0.0020	1.790	0.0179	2.89	1.73	1.31	0.78
31	4.27	256.36	1.84	0.0184	0.20	0.0020	2.475	0.0247	2.89	1.73	1.53	0.92
32	5.98	358.90	1.32	0.0132	0.20	0.0020	2.475	0.0247	2.06	1.24	1.13	0.68
33	9.97	598.17	0.79	0.0079	0.20	0.0020	2.475	0.0247	1.24	0.75	0.65	0.39

The results are summarized in Figure 24, Figure 25, Figure 26, and Figure 27. Figure 24 and Figure 25 illustrate the overall performance of this cell in terms of the relationship between energy recovery and clean coal ash, and energy recovery and product sulfur respectively.

The energy recovery was essentially constant over the range of flow rates tested (0.7 to 1.84 cm/s). The clean coal ash content was in the range of 8-9%, and energy recovery was approximately 78% for an aeration rate of 1.8 cm/s and 88% for an aeration rate of 2.5 cm/s. Again, the results suggest that a froth loading of 0.93 tph/m^2 (1.55 gm/min/cm^2) can be achieved, but it is not known whether this value would apply to more dilute feed slurries at higher feed rates of say 3.7 cm/s.

Figure 27 and Figure 26 illustrate the overall performance of this cell in terms of the relationship between energy recovery and ash rejection, and energy recovery and total sulfur rejection respectively.

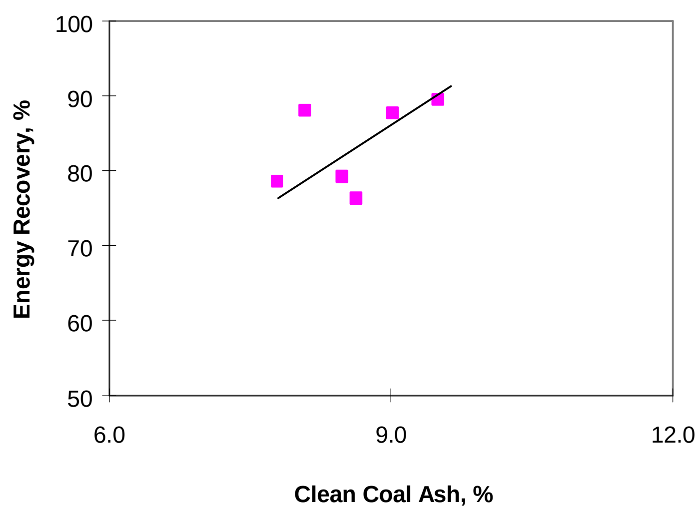

Figure 24. Open Column: Energy Recovery vs. Clean Coal Ash (Tailings Sample)

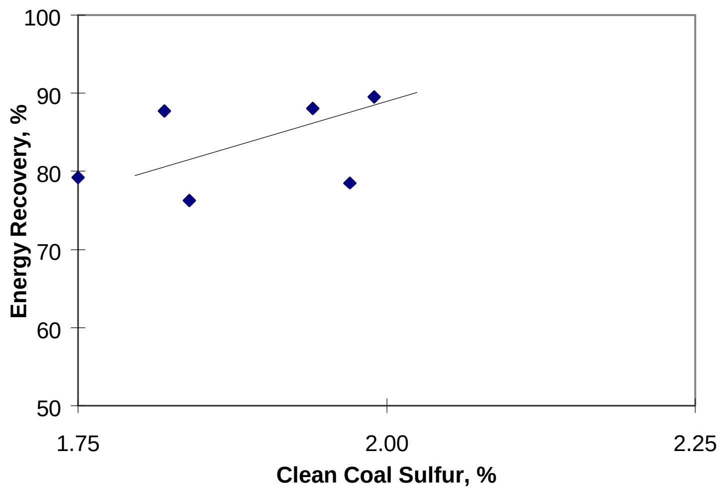

Figure 25. Open Column: Energy Recovery vs. Product Sulfur (Tailings Sample)

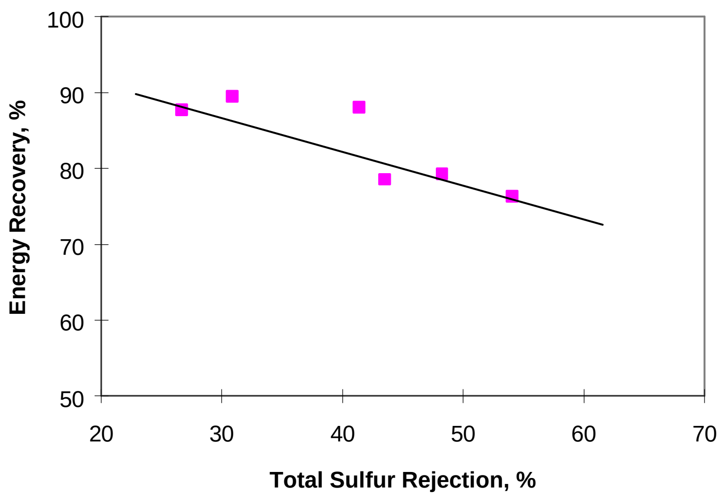

Figure 26. Open Column: Energy Recovery vs. Sulfur Rejection (Tailings Sample)

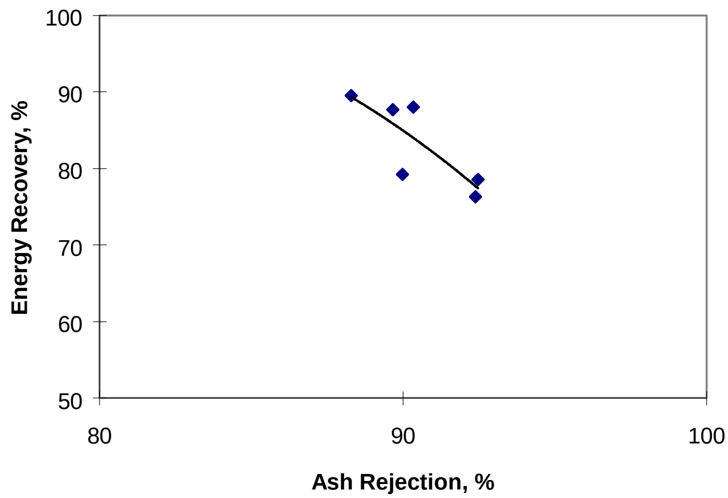

Figure 27. Open Column: Energy Recovery vs. Ash Rejection (Tailings Sample)

5.5.7 Recommended Operating Conditions

The recommended conditions based on the bench-scale test results are shown in Table 45 and Table 46.

Table 45. Open Column: Recommended Single-Stage Operating Conditions

Parameter	Value
Feed Velocity	1.8 cm/s (3.5 ft/min)
Aeration Rate	2.4 cm/s (4.7 ft/min)
Fuel Oil	1 kg/ton (2 lb/ton)
Frother	0.5 kg/ton (1 lb/ton)
Froth Mass Loading	1.2 tph/m^2 (2.0 gm/min/cm^2)
Retention Time, minimum	2 min

Table 46. Open Column: Recommended Second-Stage Operating Conditions

Parameter	Value
Feed Velocity	4 cm/s (7.8 ft/min)
Aeration Rate	2.2 cm/s (4.5 ft/min)
Fuel Oil	1 kg/ton (2 lb/ton)
Frother	0.7 kg/ton (1.4 lb/ton)
Froth Mass Loading	1.3 tph/m^2 (2.0 gm/min/cm^2)
Retention Time, minimum	2-4 min

6.0 CONCEPTUAL DESIGN

This section outlines the procedures and assumptions used for the conceptual design of the eight advanced flotation circuits selected for evaluation in this task. Aspects of the conceptual design including scale-up, material balances, process instrumentation and control, and ancillary requirements are discussed. The following eight circuits are included for analysis and evaluation:

Single-Stage Operation	**Two-Stage Operation**
Jameson Cell	Jameson/Open Column
Outokumpu HG Tank Cell	Jameson/Packed Column
Open Column	Outokumpu/Open Column
Packed Column	Outokumpu/Packed Column

6.1 Design Procedures

A computer spreadsheet model was developed and used to evaluate each advanced circuit. Bench-scale test results were scaled-up to commercial size and used as the basis for material balance and equipment sizing calculations. Using the material balance and equipment sizes, capital and operating cost estimates were prepared for each advanced circuit. Following this, an economic analysis was performed based on the PETC economic model developed by Eos Technologies, Inc. which is based on levelized, discounted cash flow principles.

Various operating conditions (i.e., different points on the grade/recovery curve) were evaluated and economically optimal conditions were selected for inclusion in the conceptual design. This evaluation was performed using two optimization criteria. The first criterion considered the circuit as a stand-alone entity during evaluation and is referred to as the circuit-optimized approach. The second criterion considered the effects of the circuit on the remainder of the preparation plant flowsheet and is called the plant-optimized approach. In this approach, any overall yield or recovery gains made on a plant-wide basis as a result of a more effective operation in the flotation circuit are credited to it during economic analysis.

6.2 Scale-Up to Commercial Scale

The bench-scale test work formed the basis for predicting full-scale equipment size and performance and associated capital and operating costs. The scale-up assumes that the slurry solids concentration and coal size consist and flotability are similar to properties tested during the bench-scale test work. Scale-up procedures were developed specifically for each flotation machine after consultation with the equipment vendors and a review of scale-up methods presented in the literature for similar equipment. The scale-up parameters of interest are: circuit flotation performance, reagent dosage, air consumption, residence time, and wash water consumption. Each of these scale-up parameters is discussed below for all circuits.

The full-scale circuit performance, with respect to energy recovery and ash and sulfur rejection, was projected to be equal to the bench-scale results. The fuel oil dosage was also assumed to be constant on a kg/t (lb/ton) basis. The frother dosage was assumed to be constant on a mass concentration basis (constant ppm frother in slurry) which is proportional to a kg/t basis if the solids concentration is held constant. Wash water is assumed to be equal to the product of the wash water superficial velocity (cm/s) as measured from the bench-scale tests and the commercial-scale cross-sectional area at the froth discharge.

The other scale factors are discussed below for each cell.

Jameson Cell

- The capacity of each downcomer is set by fixing the slurry velocity to a constant value as required to achieve proper jet operations. This value is approximately 40-45 cm/s (1.3-1.4 ft/sec).
- The ratio of the downcomer area to the froth tank surface area was initially fixed to a ratio of 2.8% and was established during development of the machine. After completion of the parametric tests, this ratio was increased to 6.25% for the high capacity tests.
- The aeration rate is set equal to the product of the air superficial velocity determined in the bench-scale tests and the cross-sectional area of the froth tank at the lip discharge. This can be achieved by induced suction created by the downcomer orifice.
- Froth mass loading: The maximum froth removal for this cell is estimated from mass loadings achieved during the bench-scale tests. The maximum froth mass flow is estimated at 0.9 tph/m^2 (1.5 g/min/cm^2) for high-recovery single-stage operation. For high- capacity, first-stage operation, a froth loading of 2.7 tph/m^2 (4.5 g/min/cm^2) was achieved.
- Power requirements (excluding air compression) are related to achieving 0.13 MPa (20 psi) pressure at the downcomer inlet. It has been assumed that 6 m (20 ft) of head can be achieved by elevation differences and the remainder must be achieved by pumping.

Outokumpu Tank Cell

- Residence time: Determined by estimation of flotation kinetics as calculated from testing two flow rates. The residence time is estimated at 150 seconds (2.5 minutes).
- Froth mass loading: The maximum froth removal for each cell is estimated from mass loadings achieved during the bench-scale tests. The maximum froth mass flow is estimated at 1.1 tph/m^2 (1.8 g/min/cm^2).
- The aeration rate is set equal to the product of the air superficial velocity determined during the bench-scale tests (2.3 cm/s) and the cross-sectional area between the froth cone and lip at the discharge.

Packed Column

- Volumetric scaleup: The vendor recommends a volumetric scale-up to adjust between changes in cell dimensions. The proportion of the cell filled with froth or slurry would also be scaled proportionately. For instance, doubling the cell height would increase capacity by a factor of two provided that the froth depth is proportionately increased or doubled. This scale-up does not address froth mass loading and has been validated only for base metal applications where froth mass loading is not critical. A modified scale-up procedure has been applied that is more conservative in estimating the required cross-sectional flotation area. The scale-up is established by assuming that doubling the height of the cell would lead to only a 50% increase in cell capacity.
- Residence time: The minimum slurry residence time is set by the time required to achieve high energy recovery. This is estimated to be 2 minutes for single- and second-stage applications. A longer residence time will be used, if required, to satisfy the froth mass loading constraint.
- Froth mass loading: The maximum froth removal as estimated from mass loadings achieved during the bench-scale tests. The maximum froth mass loading for a raw coal feed was set at 1.8 tph/m^2 (3.0 gm/min/cm^2) for a column height of 366 cm (12 ft) and 2.7 tph/m2 (4.5 gm/min/cm^2) for a column height of 732 cm (24 ft). The maximum forth mass loading for second stage operation (high ash feed) was 1.2 tph/m2 (2 gm/min/cm^2) and 1.8 tph/m2 (3.0 gm/min/cm^2) for a column height of 366 cm (12 ft) and 732 cm (24 ft), respectively.
- The aeration rate is set equal to the product of the air superficial velocity determined during the bench-scale tests (5.2-4.1 cm/s) times the height scale-up factor and cross-sectional area. This represents proportioning the air flow rate with the froth mass loading, i.e., the same solids loading on the air bubbles.

Open Column

- Residence time: Based on the slurry residence time required for high energy recovery when not mass-loading-limited. Residence time is estimated to be 2 minutes for single- and 4.3 minutes for second-stage applications. A longer residence time will be used, if required, to satisfy the froth mass loading constraint.

- Froth mass loading: The maximum froth removal as estimated from mass loadings achieved during the bench-scale tests. The maximum froth mass flow is estimated at 1.2 tph/m^2 (2.0 g/min/cm^2) for raw coal and second stage feed coal.
- The aeration rate is set equal to the product of the air superficial velocity determined in the bench-scale tests (2.4 cm/s) and the cross-sectional area.

6.3 Material Balances

The conceptual design of the optimal fine coal cleaning circuit assumes a Pittsburgh No. 8 feedstock. The plant feedstock analysis is provided in Table 47. Analyses for the +100M size fraction are used for the plant-optimization case.

Table 47. Assumed Plant Feedstock Analysis (dry basis)

Size	Wt. Fraction %	Ash %	HHV Btu/lb	Total Sulfur %
2" x 10 M	71.5	23.0	11,805	1.10
10 x 100M	22.3	20.0	12,255	1.10
100M x 0	6.3	20.0	11,911	1.10
Composite	100.0	22.1	11,933	1.10

The feed conditions assumed are based on plant performance data as presented in Table 19 in Section 4. The circuit feed rate was set at 76 tph with a solids content of 3.35%.

Four single-stage configurations and four two-stage rougher-scavenger configurations of the advanced circuit were considered in the conceptual design and economic evaluation. Assumed operating conditions for the advanced circuits under consideration are presented in Table 48 and Table 57. As will be discussed in Section 7, Economics, the operation of the flotation circuit is influenced by the criteria used to optimize its performance. For the purposes of this report, two criteria have been developed: (i) circuit-optimized (Table 48) and (ii) plant-optimized (Table 57). The assumed optimization criteria have a small effect on the circuit operating conditions but do not affect the sizing of the equipment. Material balances for each of the advanced circuits assuming circuit-optimized conditions are presented in Table 49 through Table 56.

Table 48. Assumed Operating Conditions (Circuit Optimized)

		One Stage Jameson	*One Stage* Outokumpu	*One Stage* Open Column	*One Stage* Packed Column	*Two Stage* Jameson/ Packed Column	*Two Stage* Jameson/ Open Column	*Two Stage* Outokumpu/ Packed Column	*Two Stage* Outokumpu/ Open Column
First Stage									
Energy Recovery	%	90.1	85.0	93.0	91.4	72.9	72.9	68.5	68.5
Yield	%	75.2	73.9	78.6	76.9	60.6	60.6	59.1	59.1
Total Sulfur Rejection	%	29.0	20.0	25.3	26.6	47.0	47.0	40.0	40.0
Clean Coal Ash	%	4.2	8.0	5.3	4.9	3.8	3.8	7.3	7.3
Residence Time	min	N/A	2.50	2.00	2.00	N/A	N/A	1.00	1.00
Frother Dosage	kg/tonne	0.54	0.48	0.27	0.51	0.30	0.30	0.45	0.45
Fuel Oil Dosage	kg/tonne	1.34	0.10	1.00	1.40	1.40	1.00	1.40	1.00
Eff. Feed Velocity	cm/s	1.4	2.1	1.0	1.0	4.6	4.6	2.1	2.1
Air Flow Rate	cm/s	N/A	2.20	2.40	6.20	N/A	N/A	2.40	2.40
Wash Water Rate	cm/s	0.17	0.25	0.2	0.28	0.78	0.78	0.25	0.25
Froth Depth	cm	0	10	76.2	35.56	55.88	55.88	10	10
Second Stage									
Energy Recovery	%					73.9	88.1	73.9	88.1
Yield	%					43.5	52.7	48.7	59.1
Total Sulfur Rejection	%					61.9	41.1	61.9	41.1
Clean Coal Ash	%					6.5	8.1	6.5	8.1
Residence Time	m					2.0	4.3	2.0	4.3
Additional Frother	kg/tonne					0	0	0	0
Additional Fuel Oil	kg/tonne					0	0	0	0
Eff. Feed Velocity	cm/s					3.0	1.8	3.0	1.8
Air Flow Rate	cm/s					4.1	2.5	4.1	2.5
Wash Water Rate	cm/s					0.28	0.2	0.28	0.2
Froth Depth	cm					12.7	76	12.7	76

Table 49. Jameson Cell: One-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			365	365	1,459			
Product	57.2	20.0	229	286	1,086	4.2	1.04	14,269
Tails	18.8	0.80	2,329	2,348	9,373	68.1	1.29	4,747

Table 50. Outokumpu Cell: One-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			454	454	1,817			
Product	56.2	20.0	225	281	1,067	8.0	1.19	13,698
Tails	19.8	0.81	2,422	2,442	9,749	54.0	0.84	6,849

Table 51. Open Column: One-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			667	667	2,668			
Product	59.7	20.0	239	299	1,134	5.3	1.03	14,100
Tails	16.3	0.62	2,621	2,637	10,533	73.9	1.34	3,890

Table 52. Packed Column: One-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			173	173	694			
Product	58.4	20.0	234	292	1,111	4.9	1.05	14,162
Tails	17.6	0.82	2,133	2,150	8,583	70.3	1.27	4,415

Table 53. Jameson Cell/Packed Column: Two-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2269	9,000	20.0	1.10	11,911
Wash Water			479	479	1,917			
Product	46.1	20.0	184	230	875	3.8	0.96	14,330
Tails	29.9	1.19	2,488	2518	10,042	45.0	1.31	8,191
Second Stage								
Feed	29.9	1.19	2,488	2518	10,042	45.0	1.31	8,191
Wash Water			121	121	485			
Product	13.0	20.0	52	65	247	6.5	1.15	13,926
Tails	16.9	0.66	2,557	2574	10,280	74.6	1.44	3,782
Combined Product	59.1	20.0	236	295	11,22	4.4	1.00	14,241

Table 54. Jameson Cell/Open Column: Two-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			479	479	1,917			
Product	46.1	20.0	184	230	875	3.8	0.96	14,330
Tails	29.9	1.19	2,488	2,518	10,042	45.0	1.31	8,191
Second Stage								
Feed	29.9	1.19	2,488	2,518	10,042	45.0	1.31	8,191
Wash Water			316	316	1266			
Product	15.8	20.0	63	79	300	8.1	1.47	13,688
Tails	14.2	0.51	2,741	2,756	11,008	86.2	1.14	2,062
Combined Product	61.8	20.0	247	309	1,175	4.9	1.09	14,166

Table 55. Outokumpu Cell/Packed Column: Two-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			44	44	175			
Product	44.9	20.0	180	225	854	7.3	1.12	13,802
Tails	31.1	1.49	2,057	2,088	8,321	38.4	1.08	9,177
Second Stage								
Feed	31.1	1.49	2,057	2,088	8,321	38.4	1.08	9,177
Wash Water			100	100	400			
Product	15.1	20.0	61	76	288	6.5	0.84	13,921
Tails	15.9	0.75	2,096	2,112	8,434	68.6	1.30	4,670
Combined Product	60.1	20.0	240	300	1,141	7.1	1.05	13,832

Table 56. Outokumpu Cell/Open Column: Two-Stage Material Balance

	Solids t/h	Solids %	Water t/h	Slurry t/h	Slurry Flow Rate gpm	Ash %	Sulfur %	HHV Btu/lb
First Stage								
Feed	76.0	3.35	2,193	2,269	9,000	20.0	1.10	11,911
Wash Water			44	44	175			
Product	44.9	20.0	180	225	854	7.3	1.12	13,802
Tails	31.1	1.49	2,057	2,088	8,321	38.4	1.08	9,177
Second Stage								
Feed	31.1	1.49	2,057	2,088	8,321	38.4	1.08	9,177
Wash Water			275	275	1,102			
Product	18.4	20.0	73	92	349	8.1	1.07	13,683
Tails	12.7	0.56	2,259	2,272	9,074	82.1	1.08	2,669
Combined Product	63.3	20.0	253	316	1,202	7.5	1.10	13,767

Table 57. Assumed Operating Conditions (Plant Optimized)

		One Stage *Jameson*	*One Stage* *Outokumpu*	*One Stage* *Open Column*	*One Stage* *Packed Column*	*Two Stage* *Jameson/ Packed Column*	*Two Stage* *Jameson/ Open Column*	*Two Stage* *Outokumpu/ Packed Column*	*Two Stage* *Outokumpu/ Open Column*
First Stage									
Energy Recovery	%	85.4	85.0	93.3	80.5	72.9	72.9	68.5	68.5
Yield	%	71.2	73.9	78.9	66.7	60.6	60.6	59.1	59.1
Total Sulfur Rejection	%	31.6	20.0	25.3	39.6	47.0	47.0	40.0	40.0
Clean Coal Ash	%	4.0	8.0	5.3	3.5	3.8	3.8	7.3	7.3
Residence Time	min	N/A	2.50	2.00	2.00	N/A	N/A	1.00	1.00
Frother Dosage	kg/tonne	0.51	0.48	0.27	0.39	0.30	0.30	0.45	0.45
Fuel Oil Dosage	kg/tonne	1.00	0.10	1.00	0.93	1.40	1.00	1.40	1.00
Eff. Feed Velocity	cm/s	1.2	2.1	1.0	3.0	1.1	1.1	2.1	2.1
Air Flow Rate	cm/s	N/A	2.20	2.40	4.20	N/A	N/A	2.40	2.40
Wash Water Rate	cm/s	0.17	0.25	0.2	0.28	0.78	0.78	0.25	0.25
Froth Depth	cm	0	10	76	139.7	55.88	55.88	10	10
Second Stage									
Energy Recovery	%					73.9	88.1	73.9	88.1
Yield	%					43.5	52.7	48.7	59.1
Total Sulfur Rejection	%					61.9	41.1	61.9	41.1
Clean Coal Ash	%					6.5	8.1	6.5	8.1
Residence Time	m					2.0	4.3	2.0	4.3
Additional Frother	kg/tonne					0	0	0	0
Additional Fuel Oil	kg/tonne					0	0	0	0
Eff. Feed Velocity	cm/s					3.0	1.8	3.0	1.8
Air Flow Rate	cm/s					4.1	2.5	4.1	2.5
Wash Water Rate	cm/s					0.28	0.2	0.28	0.2
Froth Depth	cm					12.7	76	12.7	76

6.4 Preparation Plant Effects

Adjustments were made to the overall preparation plant operation in the plant-optimized case in an effort to accurately reflect the impact that an advanced flotation circuit would have on the overall product recovery at a fixed quality. Specifically, increases or decreases in cleaned fine coal quality will cause corresponding changes in overall clean coal quality. In actual plant operations, adjustments would be made to the cleaning operation to bring the overall clean coal product back to the product specification. Table 58 lists the specifications used for the plant-optimized case. Table 59 describes the major equipment assumed to be in use for the overall preparation plant flowsheet for the plant-optimized case.

Table 58. Product Specification (As-Received Basis)

Property	Specification
Moisture	Not to exceed 8.5%
Heating Value	Not less than 13,000 Btu/lb
Ash	No specified limit but limited in practice by the heating value specification and moisture content

Table 59. Preparation Plant Flowsheet Assumptions

Capacity	1200 tph (dry basis)
Coal Supply	Pittsburgh No. 8
	Unit Operations
Coarse (2" x 10M)	Heavy media separation at S.G. ~1.6
Intermediate (10 x 100M)	Water-only cyclones with tailings reclean using spiral concentrators
Fines (-100M)	Advanced flotation: various configurations as specified

6.5 Process Instrumentation and Control

An elementary level of process instrumentation and control requirements have been assumed for each advanced circuit under consideration. The level of instrumentation and control assumed includes level control for the flotation cells, measurement of column feed rates, measurement of the air addition rate, and measurement of reagent addition rates. The level of control was determined based on a number of factors including the constant nature of coal cleaning operations, the level of instrumentation provided at similar installations, and the level of control required to operate the advanced circuit effectively.

The flotation cell level control loop consists of a single differential pressure transmitter to measure the pulp-froth interface height regulating a control valve on the column feed piping using a PID controller. Consideration was given to using a second differential pressure transmitter to obtain a better measurement of the pulp density which in turn will provide a better indication of interface height; however, it was not deemed necessary as the operation of the column is at a set volumetric loading and air addition.

Measurements of the feed rate and air addition rate to the flotation cell were also included in the instrumentation for the advanced circuit. Reagent addition was accomplished by using metering pumps which add reagent at an adjustable volumetric rate.

6.7 Ancillary Requirements

The ancillary requirements for the advanced circuit are identified below. The discussion is limited to the anticipated impact of installing an advanced flotation circuit at a conventional preparation plant. The ancillary requirements for the advanced circuit are not significantly different from those for a conventional flotation circuit used for fines processing.

6.7.1 Utilities

The process utilities required for the advanced circuit are similar to those required by a conventional flotation circuit and include electricity and process water. In general, the advanced circuit requires more electrical power than a conventional flotation process because additional energy is needed to introduce air into the cell, either through an air compressor or a blower. In the case of the Jameson cell, additional pump power is also used to develop suction for air introduction via a venturi orifice. The capital expenditure required to accommodate the increase in electrical load is estimated in the economic analysis.

Each process also requires an air supply at a pressure which depends on the flotation equipment used. However, this air is provided by process equipment and not by plant utilities. A tabulation of process air requirements is provided in Table 60.

Table 60. Process Air Requirements

Cell Type	Pressure, psig	Comments
Jameson	~0	Air inducted through downcomer
Outokumpu	5	
Packed Column	15	
Open Column	45	
Jameson/Packed Column	15	Based on packed column design
Jameson/Open Column	45	Based on open column design
Outokumpu/Packed Column	15	Based on packed column design
Outokumpu/Open Column	45	Based on open column design

6.7.2 Site

The building requirements for the advanced circuit are dependent on the size and configuration of the equipment used. For column-type equipment, ceiling height also becomes a consideration. The economic analysis assumes that a building addition to the existing plant will be constructed to accommodate the new circuit. Equipment floor space and height requirements are considered in the capital cost estimate. As a practical matter, a preparation plant replacing a conventional circuit with an advanced circuit will size equipment to utilize existing space whenever practical.

7.0 ECONOMICS

The bench-scale work presented in Section 5 demonstrates that the advanced circuits can achieve improved process performance when compared to conventional flotation processes for fine coal cleaning. However, it is necessary to assure that this process improvement is also economically viable. The assumptions, estimation procedure, cost estimates, and economic analyses for the eight selected advanced fine coal cleaning circuits are presented in this section and contrasted with conventional flotation. The economic merits of each advanced circuit configuration are determined by calculating its levelized costs for the two optimization criteria discussed earlier, i.e., on a circuit-optimized and a plant-optimized basis. Lastly, a sensitivity analysis examining the effects of process assumptions is also included.

7.1 Assumptions

The following economic evaluation assumes that the advanced circuit is to be installed at an existing coal preparation plant to process coal fines. The capital and operating costs of the equipment used to process the coarse fractions of coal are not considered. However, the production impact of the advanced circuit on coarse coal circuit operations is considered in the plant-optimized cases and any yield improvements are credited to the advanced fine coal circuit in question.

Several assumptions regarding the design basis for the advanced circuit have been incorporated in the conceptual design. These assumptions, as well as other assumptions required for the economic analysis, are presented in Table 61.

Table 61. Operating Assumptions

Annual Operating Hours	4,500 hours
Plant Feed Rate	1,200 tph dry basis
Fines Circuit Feed Rate	76 tph dry basis
Plant Life	20 years
Royalties	none
Financing	100% equity
Construction Duration	1 year
Inflation Rate	4%
Corporate Tax Rate	38%
Rate Of Return	25%

It was assumed that the circuit will be constructed at an existing preparation plant and that the plant will have sufficient land for constructing the building for it.

7.2 Purchased Equipment

The costs for major plant equipment items and their power requirements are based on vendor quotations, prices of similar equipment, and estimating guidelines. The costs are reported in 1995 dollars. Selection and scale-up of major plant equipment is discussed below.

7.2.1 Jameson Cell

For the conceptual plant design, the Jameson Cell Model 6000/10 was selected. For a single-stage configuration, four cells are required. Each cell is approximately 6 meters long by 2 meters wide and is priced at $159,500, including remote instrumentation and controls. The shipping weight of each cell is 31,739 lb.

For first-stage operation, 16 m^2 of froth tank area was assumed and the cost was calculated proportionately.

7.2.2 Outokumpu Cell

The Outokumpu Tank Cell Flotation Unit Model TC 10 was selected for the conceptual plant design. For a single-stage configuration, two lines of cells containing four cells each were required (12.5 minutes residence time). The cost of all eight units is $320,000 and includes instrumentation, controls, and air supply equipment. A blower with a blower motor is used to supply air to the cells.

For first-stage operation, a 1-minute residence time was assumed on three Model TC 10 cell.

7.2.3 Open Column

For the open column single-stage design, four 12-ft diameter by 20-ft tall flotation column cells from Pyramid Resources were selected. Each column costs $92,400 F.O.B. and includes a sparger system, wash water system, and level control.

For second-stage operation, 33 m^2 of column cell area was assumed based on the scale-up criteria given in Section 6.2, or approximately one-third of the single-stage area. The cost was calculated accordingly.

7.2.4 Packed Column

Two GL&V self-supported packed columns, 8 ft by 12 ft by 24 ft high, were selected for the single-stage design of the packed column circuit. Each column costs $220,300 F.O.B. and includes distributors for feed inlet, air inlet, and wash water. Instrumentation was not included in the cost estimate for this item and was assumed to be $35,000.

For second-stage operation, 11 m^2 of column cell area was assumed (see Section 6.2), and the cost was proportioned accordingly.

7.2.5 Cost Scaling

Equipment costs for cells and columns with sizes different than those presented above were scaled proportionally to flotation area. This scaling represents the fact that multiple equipment items were used in the design and variations in required area from the base equipment can be accommodated by purchasing additional (or fewer) units. Cell and column heights were assumed constant in the conceptual design.

7.3 Capital Costs

Capital costs such as installation, structures, piping, instrumentation other than cell instrumentation, and foundations were estimated directly based on the scope of work and were not factored from purchased equipment costs. Flotation cell/column instrumentation costs were included in the purchased cost of the equipment. Electrical costs were estimated taking into account the gross electrical requirements of each circuit. Building construction costs were estimated on the basis of the floor plan area required by each circuit. Indirect capital costs were then estimated from the total direct fixed costs. The bases used to estimate direct and indirect capital costs are summarized in Table 62.

Table 62. Direct and Indirect Cost Estimation

Cost Item	Basis for Estimation
Direct Costs	
Purchased Equipment	Manufacturer's estimate
Installation	Direct estimate
Piping	Direct estimate
Instrumentation	Direct estimate*
Electrical	Determined by electrical needs
Buildings	Determined by equipment size
Indirect Costs	
Engineering	25% of direct costs

* Does not include cell instrumentation which is included in the flotation cell/column equipment cost

7.4 Operating Costs

7.4.1 Utilities

Electrical power consumption was estimated for each item in the equipment list. Power costs were estimated using an industrial rate of $0.05/kW-hr.

7.4.2 Consumables

The consumables used in the advanced flotation circuit are shown in Table 63. The dosages and addition rates of each item vary depending on the process. Details on the addition rates are provided in the material balance presented in Section 6.

Table 63. Unit Costs for Consumables

Item	Unit Cost
Frother	$0.64/lb
Fuel Oil No. 2	$0.10/lb
Flocculant	$0.90/lb

7.4.3 Personnel

It is estimated that manpower requirements for operation of the advanced circuit will be similar to those for operation of a conventional flotation circuit. Personnel requirements and associated annual costs are summarized in Table 64.

Table 64. Personnel Requirements

Position	Operator	Maintenance
Salary	\$35,000	\$45,000
Benefits	50% of salary	50% of salary
Shifts per day	2	2
Utilization	25%	5%
Annual cost	\$26,250	\$6,750
Total Annual Cost	\$33,000	

For purposes of the economic evaluation, there is no net gain or loss in manpower when comparing the advanced flotation circuit and the conventional flotation circuit.

7.4.4 Maintenance

Annual equipment maintenance costs were estimated to be 5% of the purchased equipment cost for each advanced circuit.

7.5 Circuit-Optimized Economics

Each of the advanced circuits was evaluated as a stand-alone entity using the PETC economic model developed by Eos Technologies, Inc. Levelized incremental product costs were calculated on a \$/ton and \$/MMBtu basis. Also, desulfurization costs were calculated on a \$/ton of SO_2 removed basis. The circuit-specific input data set used for the economic model is provided in Table 65.

Table 65. Economic Model Inputs (Circuit-Optimized)

		One Stage *Jameson*	One Stage *Outokumpu*	One Stage *Open Column*	One Stage *Packed Column*	Two Stage *Jameson/ Packed Column*	Two Stage *Jameson/ Open Column*	Two Stage *Outokumpu/ Packed Column*	Two Stage *Outokumpu/ Packed Column*
Direct Processing	$x1000	1,011	547	823	790	816	923	648	761
Emission/Waste Equipment		0	0	0	0	0	0	0	0
Off-Site Utilities		0	0	0	0	0	0	0	0
Total Direct Capital	$x1000	1,011	547	823	790	816	923	648	761
On-Site Assembly	$x1000	142	142	142	142	142	142	142	142
Working Capital		0	0	0	0	0	0	0	0
Engineering	$x1000	288	172	241	233	239	266	197	226
Contingency		0	0	0	0	0	0	0	0
Site Modifications		0	0	0	0	0	0	0	0
Total Indirect Capital	$x1000	430	314	383	375	381	408	339	367
Expensible Capital		0%	0%	0%	0%	0%	0%	0%	0%
Fixed O&M	$x1000	99	66	84	85	83	91	73	80
Variable O&M	$x1000	741	481	598	758	649	691	685	721
Ins. & Prop. Tax/yr.		0	0	0	0	0	0	0	0
PLANT DATA									
Plant Capacity Factor	%	51.3	51.3	51.3	51.3	51.3	51.3	51.3	51.3
Coal Input	tons/hr	76.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0
Heating Value	Btu/lb	11911	11911	11911	11911	11911	11911	11911	11911
Sulfur	%	1.10	1.10	1.10%	1.10	1.10	1.10	1.10	1.10
Coal Output	tons/hr	57.2	56.2	59.7	58.4	59.1	61.8	60.1	63.3
Heating Value	Btu/lb	14,269	13,698	14,100	14,162	14,241	14,166	13,832	13,767
Sulfur	%	1.04	1.19	1.05%	1.05	1.00	1.09	1.05	1.10

The results of the economic analysis are presented in **Table 66** and **Table 67**.

Table 66. Single-Stage Economic Results (Circuit-Optimized)

	Conventional Flotation	Jameson	Outokumpu	Open Column	Packed Column
Levelized Product Costs					
Incremental, $/MMBtu	0.201	0.206	0.198	0.158	0.182
Total, $/MMBtu	0.79	0.79	0.79	0.74	0.77
Total, $/ton	21.71	22.63	21.51	21.00	21.78
Desulfurization, $/ton SO_2	3,158	897	3,108	740	854
Energy recovery, %	85.0	90.1	85.0	93.0	91.4
Clean coal ash, %	7.5	4.2	8.0	5.3	4.9

Table 67. Two-Stage Economic Results (Circuit-Optimized)

	Conventional Flotation	Jameson/ Packed Column	Jameson/ Open Column	Outokumpu/ Packed Column	Outokumpu/ Open Column
Levelized Product Costs					
Incremental, $/MMBtu	0.201	0.162	0.142	0.163	0.138
Total, $/MMBtu	0.79	0.75	0.73	0.75	0.73
Total, $/ton	21.71	21.33	20.65	20.75	19.96
Desulfurization, $/ton SO_2	3,158	631	788	836	967
Energy Recovery, %	85	92.9	96.8	91.8	96.3
Clean Coal Ash, %	7.5	4.4	4.9	7.1	7.5

The above single-stage circuit-optimized results indicate that both column cells will result in lower costs than a conventional flotation circuit. The open column costs were the lowest for the single-stage configuration. In the case of two-stage operation, all four circuits were more economical than the conventional circuit.

The results of the circuit-optimized economic analysis correspond with the overall energy recovery, as expected. The energy recovery value correlates to the clean coal ash content in that tests with lower product ash contents also have lower energy recoveries. The problem with a circuit-optimized approach is that no constraints on product quality have been introduced and that the tests being compared are at different points on the grade/recovery relationship. If the fine coal circuit results represented a final product, then price adjustment factors could, in general, be applied to compensate for changes in product quality. Price adjustments (price premiums) have been computed for each circuit-optimized case to determine the break-even levelized production cost for each circuit. The Outokumpu/open column circuit, which has the lowest circuit-optimized levelized cost, was selected as the base case. Annual revenue requirements were computed for the other circuits that resulted in the same levelized cost as the Outokumpu/open column case. Table 68 summarizes the price premiums required to achieve the break-even production cost. For instance, the open column case will produce a clean coal product with an energy content that is 332 Btu/lb higher than the Outokumpu/open column case and requires an increase in revenues of $0.016/MMBtu to achieve the break-even levelized cost of $0.73/MMBtu. The issue is whether the marketplace would support a 1.6¢/MMBtu premium for coal with a 332 Btu/lb higher calorific value.

Table 68. Calculated Price Premium for Break-Even Levelized Production Costs

Incremental Levelized Production Cost = $0.14/MMBtu, levelized product cost = $0.73/MMBtu

Circuit	**Product Ash %**	**Product Btu/lb**	**Increase in Revenue Requirement $x1000/yr**	**Price Premium $/MMBtu**	**Btu/lb Increase**
Conventional Flotation	7.50	13,772	375	0.054	5
Jameson	4.16	14,269	423	0.058	502
Outokumpu	8.00	13,698	350	0.051	-70
Open Column	5.30	14,100	124	0.016	332
Packed Column	4.88	14,162	273	0.037	395
Jameson/Packed Column	4.39	14,241	149	0.020	474
Jameson/Open Column	4.89	14,166	22	0.003	399
Outokumpu/Packed Column	7.10	13,832	156	0.021	65
Outokumpu/Open Column	7.53	13,767	0	0	0

However, discussing the relative merits of producing high-calorific fine coal tends to oversimplify the economics of fine coal cleaning. In the case of existing coal preparation plants, the recovered fines will always be blended with the coarse coal product. Therefore, operation of the fine coal circuit is dependent upon the quality of the coal from the coarse coal circuit in addition to the contract specifications for coal quality. The following section modifies the economics presented above to consider the total coal product as the basis for economic comparisons.

7.6 Plant-Optimized Economics

Each of the eight advanced circuits was reevaluated using the PETC economic model. However, the operating conditions were selected using a different criterion for defining optimal economic performance, termed plant-optimized economics. The goal is to derive operating conditions simultaneously for the fine coal circuit and other circuits in the plant such that the levelized costs of producing the plant product are minimized. This approach assumes that the fine coal circuit is constructed at an existing plant. Plant-optimized economic performance includes the operating and capital costs of the advanced circuit, energy recovered from the advanced circuit, and additional energy recovery (or losses) from changes in coarse coal circuit operations.

A model of the coal preparation plant has been used as a basis for all recovery calculations. The analysis is presented in a similar fashion to the circuit-optimized cases. A key difference between the plant-optimized and the circuit-optimized criteria is that a coal quality specification for the plant clean coal is specified for the plant-optimized case and the operation of each plant circuit is adjusted to produce the overall clean coal specification at maximum profits. In the case of the plant in question, the clean coal specification is for a 13,000 Btu/lb product on an as-received basis.

The plant-optimized approach was to evaluate each bench-scale test using a plant model. The model computed the effect of changes in the coarse coal separating gravity required to produce the specified product quality on total plant recovery. The levelized costs were then based on the net change in energy recovery from the coarse circuit in addition to the recovery from the fine circuit. The model assumes no change in the middle size fraction spiral/ water-only-cyclone circuit. The bench-scale test result which produced the lowest levelized costs was assumed to be the optimal operating condition. This approach does not rely on extrapolations of cell performance but it does restrict the evaluation to range in energy recovery measured from the test work. Using this approach, the optimal conditions and associated levelized costs were found for each of the eight circuits.

The flotation circuit-specific input data set used for the plant-economic model is provided in Table 69. The results of the economic analysis are presented in Table 70 and Table 71.

Table 69. Economic Model Inputs (Plant-Optimized)

		One Stage *Jameson*	One Stage *Outokumpu*	One Stage *Open Column*	One Stage *Packed Column*	Two Stage *Jameson/ Packed Column*	Two Stage *Jameson/ Open Column*	Two Stage *Outokumpu/ Packed Column*	Two Stage *Outokumpu/ Packed Column*
Direct processing		968	547	724	738	816	923	648	761
Emission/Waste equipment		0	0	0	0	0	0	0	0
Off-site utilities		0	0	0	0	0	0	0	0
Total direct capital		968	547	724	738	816	923	648	761
On-site assembly		142	142	142	142	142	142	142	142
Working capital		0	0	0	0	0	0	0	0
Engineering		277	172	216	220	239	266	197	226
Contingency		0	0	0	0	0	0	0	0
Site modifications		0	0	0	0	0	0	0	0
Total indirect capital		419	314	358	362	381	408	339	367
Expensible capital		0%	0%	0%	0%	0%	0%	0%	0%
Fixed O&M		96	66	77	81	83	91	73	80
Variable O&M		666	480	694	567	649	691	685	721
Ins. & property tax/yr.		0%	0%	0%	0%	0%	0%	0%	0%
PLANT DATA									
Plant capacity factor	%	51.3	51.3	51.3	51.3	51.3	51.3	51.3	51.3
Coal input	tons/hr	76.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0
Heating value	Btu/lb	11,911	11,911	11,911	11,911	11,911	11,911	11911	11911
Sulfur	%	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Coal output	tons/hr	63.9	53.6	63.7	62.2	63.2	60.8	54.9	58.1
Heating value	Btu/lb	13,641	13,823	13,671	13,762	13,999	14,222	14,073	13,989
Sulfur	%	1.17	1.19	1.17	1.08	1.04	1.09	1.04	1.10

Table 70. One-Stage Economic Results (Plant-Optimized)

	Conventional Flotation	**Jameson**	**Outokumpu**	**Open Column**	**Packed Column**
Levelized Product Costs					
Incremental, \$/MMBtu	0.201	0.147	0.228	0.134	0.138
Total, \$/MMBtu	0.79	0.73	0.81	0.72	0.72
Total, \$/ton	21.71	20.01	22.52	19.70	19.95
Desulfurization, \$/ton SO_2	3,158	1,901	3,065	1,745	865
Energy recovery, %	85.0	85.4	85.0	86.0	87.2
Clean coal ash, %	7.5	4.0	8.0	4.1	4.9

Table 71. Two-Stage Economic Results (Plant-Optimized)

	Conventional Flotation	**Jameson/ Packed Column**	**Jameson/ Open Column**	**Outokumpu/ Packed Column**	**Outokumpu/ Open Column**
Levelized Product Costs					
Incremental, \$/MMBtu	0.201	0.125	0.152	0.219	0.190
Total, \$/MMBtu	0.79	0.71	0.74	0.81	0.78
Total, \$/ton	21.71	19.95	21.01	22.70	21.73
Desulfurization, \$/ton SO_2	3,158	586	813	1,021	1,203
Energy recovery, %	85.0	92.9	96.8	91.8	96.3
Clean coal ash, %	7.5	4.4	4.9	7.1	7.5

The plant-optimized analysis results in a different operational perspective for fine coal circuit operations. This approach penalizes the inclusion of ash and water with the fines and promotes the recovery of coarse middlings particles if higher overall plant recoveries result. As a result, lower levelized production costs are realized for the Jameson/packed column than for the circuit-optimized approach ($0.125 vs. $0.142/MMBtu) despite the fact that no change has taken place in its performance. This improvement in levelized production costs results from increasing the coarse coal yield which was made possible by the low ash product from the advanced flotation circuit. In Table 72 the levelized incremental costs given in Table 70 and Table 71 are subdivided into the three major cost categories for coal cleaning processes in order to analyze them more thoroughly:

- Energy loss: loss of heating value in the refuse
- Operating costs: annual costs associated with circuit operations
- Capital costs: costs for construction of the circuit.

The operating costs are in the range of $0.054-$0.071/MMBtu and the capital costs are in the range of $0.043-$0.062/MMBtu. The major difference in costs is related to the energy loss costs. The energy loss cost is calculated on a net plant loss basis. It is determined by calculating the loss of energy content from the flotation circuit minus the incremental energy recovered from the coarse circuit by raising the media gravity. It reflects the full impact of installing each flotation circuit on annual energy losses from the plant. The energy losses are high for the Outokumpu cell because of the relatively high-ash product (8% vs. 7.5% ash from a conventional circuit) produced which results in an additional loss of coal from the coarse coal circuit. The lowest energy loss, on a plant-wide basis, is for the Jameson/packed column circuit which has both high recovery and low product ash.

Table 72. Levelized Incremental Cost Breakdown

	Conventional Flotation	Jameson	Outokumpu	Open Column	Packed Column	Jameson/ Packed Column	Jameson/ Open Column	Outokumpu/ Packed Column	Outokumpu/ Open Column
Btu loss cost, $/MMBtu	0.107	0.022	0.130	0.023	0.031	0.014	0.028	0.101	0.066
Operating cost, $/MMBtu	0.054	0.066	0.055	0.065	0.055	0.062	0.071	0.061	0.066
Capital cost, $/MMBtu	0.045	0.059	0.043	0.046	0.045	0.050	0.062	0.047	0.057
Btu loss cost, % of total	52.2	15.3	57.0	17.1	23.6	11.1	17.3	48.2	35.1
Operating cost, % of total	26.1	44.7	24.2	48.6	42.4	49.0	44.1	29.1	34.7
Capital cost, % of total	21.7	40.1	18.8	34.3	34.1	39.9	38.6	22.7	30.2

Optimal operation of the flotation circuit has been shown to depend on the properties of the coal and operation of the other circuits. The plant model used in this analysis is representative of the plant conditions for the project coal sample. However, as described in the following section, changing the coal property assumptions alters the conditions for optimal flotation operations.

7.7 Sensitivity Analysis

The process economics for each circuit are based on a number of estimates and assumptions. Both cost and process parameter assumptions can have a significant impact on levelized costs. In an effort to better quantify the effect of these assumptions, two series of sensitivity analyses were performed. First, changes in capital and operating costs are considered, followed by changes in the plant parameters used in the economic model.

A two-stage Jameson/packed column configuration was selected to conduct the sensitivity analysis for capital and operating costs. The base case costs (shown in Table 69) were $1.2 million for capital costs and $0.732 million for annual operating costs, which led to a levelized incremental cost of $0.125/MMBtu. These costs have been varied as shown in Table 73 to assess the change in incremental levelized cost. An increase of $200,000 in the capital costs or an increase of $150,000/yr in operating costs results in an increase in the levelized incremental costs by $0.01/MMBtu. These changes are equivalent to a 17% and 20% increase in the capital and operating costs, respectively. The capital and cost estimate would be expected to be in this range or have a ± $0.01/MMBtu incremental levelized cost.

Table 73. Capital and Operating Cost Sensitivity

	Base	Capital Cost Change			Operating Cost Change		
	Case	*+200K*	*+400K*	*-200K*	*+100K*	*+200K*	*-100K*
Levelized Incremental Cost, $/MMBtu	0.125	0.135	0.145	0.114	0.132	0.140	0.117

The second sensitivity analysis to be considered is the impact of plant parameters. The plant parameters are an integral part of the optimization process because the parameters indirectly determine the optimal grade/recovery operating point for the flotation circuit. On average, the clean coal quality at the Emerald mine coincides with the product specifications (13,000 Btu/lb (as-received) at 8% moisture). However, to construct a plant model several assumptions were required that are not normally measured, such as minus 100-mesh clean coal moisture. Parameter estimates were based on available plant data and experience at similar coal preparation plants where necessary. In an effort to better understand the plant-optimized process, a sensitivity analysis was performed to evaluate the effects of moisture and ash distribution assumptions on the optimal energy recovery from the fines circuit.

The plant parameter sensitivity analysis requires prediction of fine coal flotation over a wide range in energy recovery. The bench-scale data provide a measure of the grade/recovery curve for each of the circuits considered but do not provide a consistent trend for this relationship over the required range needed for sensitivity analysis to ensure optimal operations. A two-stage flotation model has been constructed to estimate flotation circuit performance as a means of providing a consist grade/recovery relationship. The model assumes that the Jameson cell is used for the first stage and a column cell is used for the second stage. The column cell could be either an open or a packed column since the performance of these cells was essentially the same except that the packed column was operated at a slightly lower energy recovery point (with lower clean coal ash) than the open column during testing of second-stage operation.

The two-stage model first uses the raw coal washability to define the raw coal grade/recovery relationship (Figure 28). The recovery from the Jameson cell (first stage) is then related to frother concentration, as shown in Figure 29. The column cell recovery is modeled as a function of cell residence time and frother concentration. The range of frother concentration considered was 6-16 ppm and the range of residence time was 1-6 minutes. The column model is based on first-order flotation kinetics with the flotation rate constant set proportional to frother concentration. The model was fitted to the bench-scale column test results for the tailings coal sample by adjustment of two model constants. Using the given residence time and frother concentration, the column recovery is computed. The total circuit recovery is then computed and the total circuit product coal ash is determined by using the raw coal model. The coal quality of the second-stage product is then determined as the difference between the total and first-stage performance. An example of how the model second-stage performance changes as a function of residence time is given in Figure 30. The importance of frother concentration for the second-stage column cell is depicted in Figure 31 with the residence time set to 4 minutes.

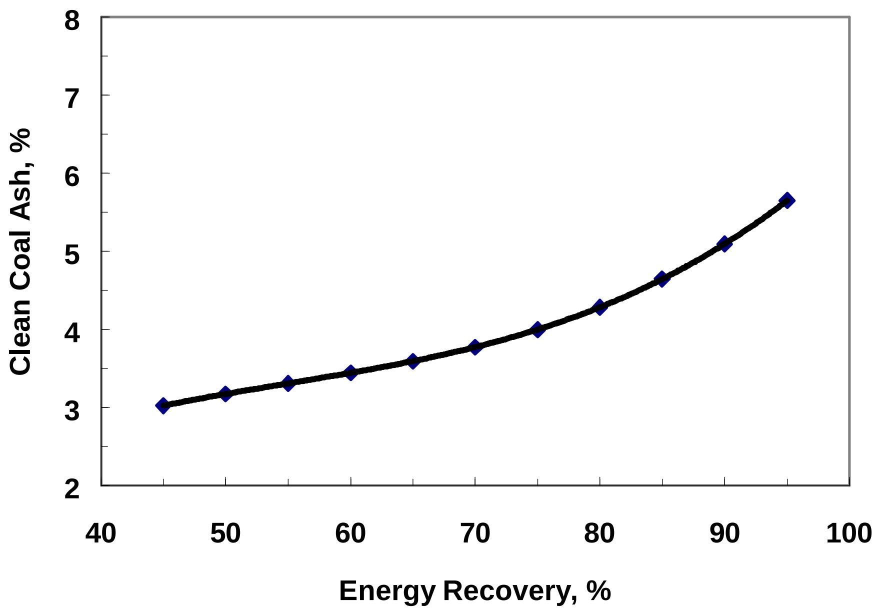

Figure 28. Model Raw Coal Energy Recovery vs. Clean Coal Ash

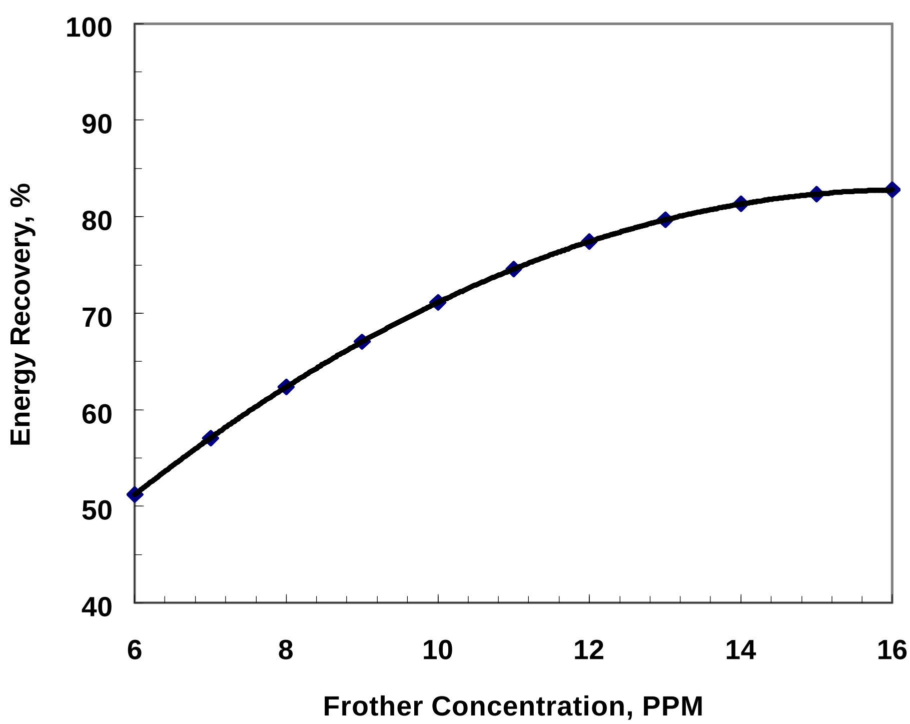

Figure 29. Model First-Stage Recovery vs. Frother Concentration

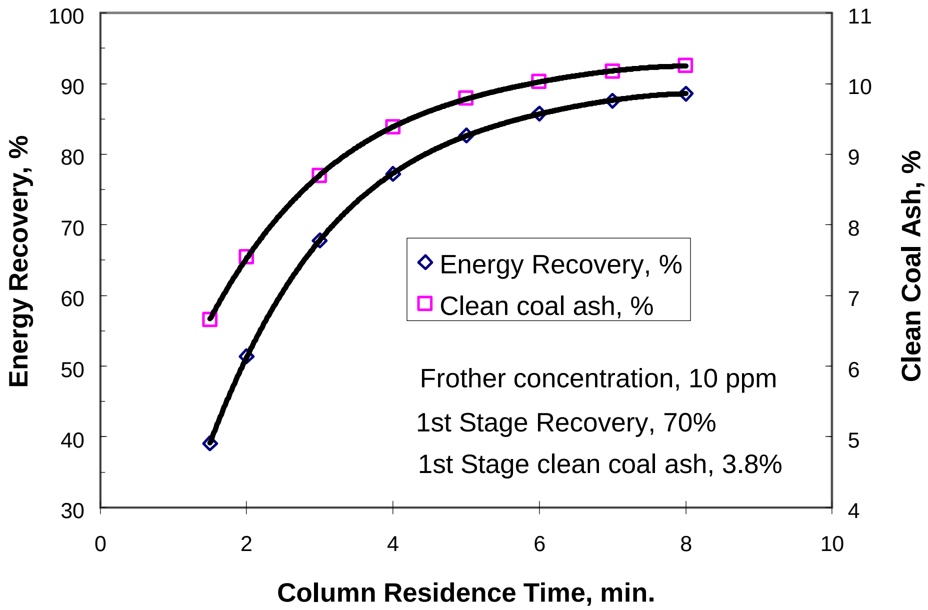

Figure 30. Model Second-Stage Column Recovery vs. Residence Time

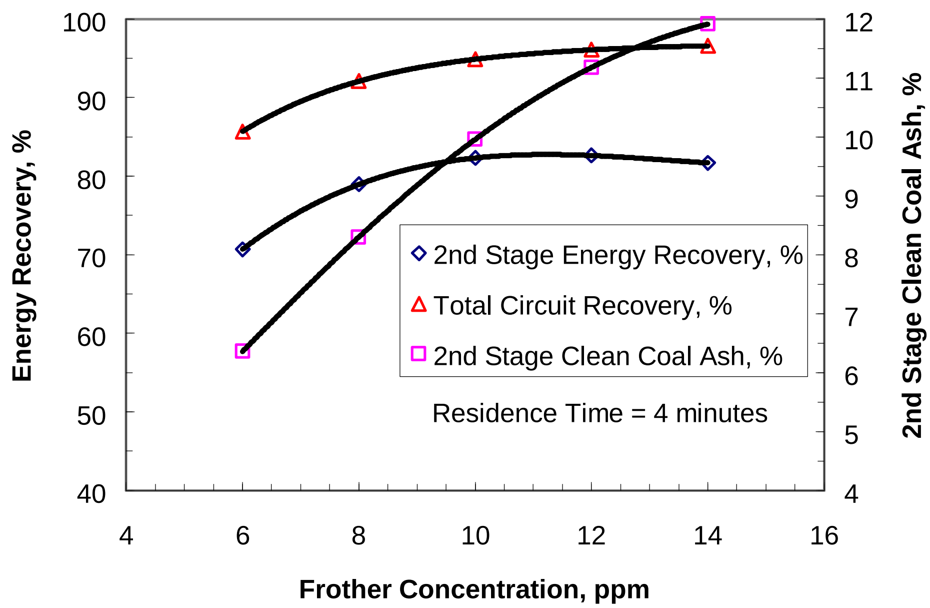

Figure 31. Model Column Recovery vs. Frother Concentration

The model was used to derive fine coal circuit performance for six cases of preparation plant model parameters. The cases shown in Table 74 represent six combinations of water and ash assumptions that produce 13,000 Btu/lb clean coal using a 1.6 separating gravity in the coarse coal circuit and conventional fine coal flotation. High and low fine coal moisture are evaluated in cases 1 and 3. For example, in case 1, the fine coal moisture is assumed to be 24.9% which requires an increase in the coarse coal moisture to 5% to achieve an 8% total product moisture. Cases 4-6 evaluate the effect of lowering the coarse coal product ash from 6.6% to 6.25% at a 1.6 separating gravity. A base case for the decreased coarse coal ash scenario is established by raising the conventional fine coal flotation recovery to 90% at 9.0% ash to again achieve the 13,000 Btu/lb total product specification. The three levels of fine coal moisture are repeated for the new ash assumptions.

For each sensitivity case, a range of frother dosage (6-16 ppm) and column cell residence times (1-6 minutes) was evaluated. The conditions that produce the lowest levelized costs for each case have been tabulated in Table 74.

Table 74. Plant Parameter Sensitivity Analysis

	Case One	Case Two	Case Three	Case Four	Case Five	Case Six (a)	Case Six (b)
Fine Coal Moisture, %	24.9	28.4	31.4	24.9	28.4	31.4	31.4
Coarse Coal Moisture, %	5.0	4.5	4.0	5.0	4.5	4.0	4.0
Coarse Coal F1.6 Ash, %	6.6	6.6	6.6	6.25	6.25	6.25	6.25
Levelized Product Cost Incremental, $/MMbtu	0.128	0.131	0.125	0.066	0.073	0.073	0.073
Optimal Conditions:							
Frother Concentration, ppm	7	6.5	6	8	6.5	6	7.5
Residence Time, min.	4	4	4	6	6	6	4
Clean Coal Ash, %	4.9	4.7	4.5	5.5	5.3	5.2	5.0
Energy Recovery, %	90	88	86	95	93	92	91

The results indicate that the optimal fine coal recovery changes depending on the plant parameters. Increasing the fine coal moisture leads to lower optimal energy recovery (see recovery trends for cases 1-3 and 4-6). When the ash content of the coarse coal is assumed to be lower, the optimal recovery from the fine coal circuit increases (cases 4-1, 5-2, and 6-3) and higher separating gravities are used in the coarse coal circuit resulting in lower levelized costs. The column cell residence time is related to the optimal energy recovery and increases from 4 to 6 minutes when recoveries above 90% are optimal. The frother dosage was low, ranging from 8 ppm to 6 ppm. The simulation suggests that the best method for increasing coal recovery is by increasing residence time and maintaining frother dosage below a level of about 8 ppm.

Since the above analysis is based on empirical simulation of a two-stage circuit, the absolute values of the model outputs, such as residence time, may not be accurate but the trend in outputs, such as optimal energy recovery decreasing with higher fines moisture is valid.

Although the base case is assumed to be the most accurate estimation of the plant conditions, these parameters are not expected to be constant during plant operations. In Section 3, conventional flotation data were shown where the product ash ranged from 6% to 9.5%. The coarse coal cumulative float 1.6 ash is known to vary. Recent drill core data suggest that the range for this ash value is 5.7% to 7.1% (12 samples). Therefore, the optimal flotation recovery over time will change with changing plant conditions. This illustrates the need for control of the flotation circuit recovery. For continuous optimal operations, the flotation circuit must be capable of achieving efficient separations over a wide range in recovery. The sensitivity analysis suggests that the recovery range required is 86% to 95% with a lower limit of 80% to 85%, given that the model becomes less accurate at lower frother concentrations because of limited test data in this region.

8.0 TWO-STAGE OPERATION

One of the major objectives of this project is to evaluate the use of two-stage circuits for an optimal flotation circuit design. The premise of the project is that column cells are froth mass loading-limited and cannot be operated at maximum feed velocities for relatively low-ash feed coals such as the Pittsburgh seam. The test work completed by Pyramid has shown that the open column is indeed froth mass loading-limited when processing the raw coal fines at 3% solids. Their work also shows that feed velocities can be substantially increased, from 1 cm/s to 1.84 cm/s, and possibly as high as 4.5 cm/sec, when a portion of the clean coal is recovered in a first-stage flotation step. The packed column tests are less conclusive with regard to froth mass loading since the maximum froth mass loading could not be determined for the 12-ft tall test column due to feed pump limitations. The test work did demonstrate that a high froth mass loading of 2.4 tph/m^2 (4 $gm/min/cm^2$) was possible with a feed velocity of 3 cm/sec for a raw coal feed. These results suggest that it is possible to devise a two-stage circuit in which both the column froth mass loading and feed velocities (residence times) are maximized by appropriate use of a two-stage circuit.

Economical use of a two-stage circuit requires that the feed velocities be higher in both flotation steps than for a comparable single-stage operation while achieving high energy recovery. Increasing the feed velocity in the first stage was shown to lead to higher froth loadings in the tests on the Outokumpu cell, where feed rates of 75.6 l/min (20 gpm) produced approximately 1.9 g/min/cm^2 loadings and feed rates of 94.5 l/min (25 gpm) produced about 2.5 g/min/cm^2, or a proportional increase in coal recovery. The high capacity tests for the Jameson cell resulted in a substantial increase in froth mass loading (4.5 vs. 1.7 gm/min/cm^2) while producing a clean coal product containing less than 4% ash. As previously noted, the tailings sample tests completed indicate that feed velocities can be also be increased for second stage operations, where residence time considerations are the constraint on capacity.

Another issue concerning two-stage operations is the consumption of reagents. A hypothesis of this project was that reagent consumption for two-stage operations could be reduced compared to a single-stage operation. The rationale for this hypothesis was that high proportion of the fine low-ash coal particles could be floated in the first stage with a small amount of reagents. Removal of this low-ash coal fraction would then allow the reagent dosage to be set appropriately for the more difficult-to-float particles in the second stage, leading to a net reduction in total reagent consumption. The two-stage Jameson cell tests showed that very high energy recoveries are possible (96%) with little or no additional reagent. Definitive confirmation of this hypothesis can only be obtained by testing a two-stage circuit directly (as is planned for the POC module). However, the test results to date are consistent with this hypothesis given the low frother concentrations (10 ppm) used in the second-stage tests.

The economics of two-stage operations, presented in Sections 6 and 7, is based on an increase in feed velocities to each stage compared to single-stage operations. In the case of the Jameson cell the feed velocity is increased from 1.3 to 4 cm/s. In the case of a column second stage, the feed velocity is increased from about 1 cm/sec to 2-4 cm/sec.

The two-stage circuits achieved the lowest levelized costs. The capital cost, however, is about $115,000 higher than that of the best single-stage operation. This suggests favorable overall economics for the two-stage operation. However, this is a very tentative analysis and two-stage pilot-scale tests must be conducted to demonstrate the validity of this concept.

9.0 EQUIPMENT SELECTION

The primary objective of the bench-scale test work was to provide data required to select the two most appropriate flotation machines for further testing at the pilot scale. During the in-plant POC pilot-scale tests, these machines will be fully characterized in single- and two-stage operations. The criteria established at the start of the project for development of a two-stage circuit were that it should:

1. Achieve a low-ash product from the first stage with high froth mass loading
2. Achieve an efficient separation in the second stage given a high-ash, dilute feed
3. Minimize operating and capital costs on a levelized cost basis.

The objective of Task 5 was to select either the Jameson or the Outokumpu cell as the first-stage flotation machine and either the packed or open column cell as the second-stage machine. After reviewing the performance data and related economics, the flotation machines and circuits recommended for pilot testing are:

- Single-stage Jameson cell
- Single-stage packed column
- First-stage Jameson cell, second-stage packed column.

The Jameson cell has been selected for the first stage based on its good performance and low operating costs since it does not require compressed air. It has also demonstrated the potential for being used as a first-stage machine by achieving the highest froth mass loading levels measured while producing a 4% ash product.

In general, the performance of both the open and packed columns was very good. Both cells achieved good process separations and demonstrated the potential for high-capacity operations with dilute feed slurries (second-stage feed conditions). Both cells were capable of producing a product with less than 4% ash from a raw coal feed. The packed column, however, demonstrated a higher capacity with the raw coal feed with corresponding higher froth mass loadings. The open column achieved higher recoveries with the high-ash feed coal (second-stage feed) but also required longer residence times than the packed column. It appears that both cells had a similar product ash/recovery relationship for the high-ash second-stage feed, and the two-stage economics for both cells is excellent. The packed column was selected in favor of the open column because of its:

- Potential for achieving high froth mass loading levels
- Potential for process control via regulation of froth depth
- Enhanced process separation efficiency when producing a low-ash product.

The packed column achieved twice the froth mass loading of the open column cell and has the potential for higher loadings. The froth depth can be adjusted over a wider range of operation than with the open column and was demonstrated to operate with depths up to 84 inches. The packed column produced the lowest ash product from the tailings sample. Overall, the packed column will provide a greater degree of testing flexibility because it can be operated over a wide range of energy recovery values at near theoretical efficiency. This is important since the economics indicated that the optimal energy recovery depends on coal parameters that have been shown to vary. Therefore, continuous optimal circuit operation will require control of energy recovery over a range of 95% to 85% and possibly as low as 80% in response to changing plant conditions.

10.0 POC DESIGN & CONSTRUCTION

A two-stage POC flotation circuit using the Jameson cell in the first stage and the packed column cell in the second stage was constructed at the coal preparation plant. The design also allowed for operation of each cell as a standalone unit (single cell operation). The Jameson cell was retrofitted with adjustable cell walls in order to alter the cell cross-sectional area, and thus have the capability to change the froth mass loading independently of the feed rate. Automatic slurry samplers were installed on each process stream and flow meters were used to measure feed coal slurry and water addition flow rates. Reagent pumps for frother and fuel oil addition were installed upstream of both cell feed pipes.

The relevant specifications of each test machine were as follows:

Jameson cell

- Downcomer inside diameter, 10.2 cm
- Downcomer length, 4.7 meters
- Net froth area, 0.1 m^2
- Submerged wash water pipe depth, 15 cm from lip height

Packed column cell

- Cell diameter, 30.5 cm
- Cell height, 7.5 meters
- Feed inlet, 3 meters from top of cell
- Packing size, nominal 1.3 cm and 1.9 cm openings

11.0 POC OPERATIONS

The POC test work was conducted over a period of eight months. The goals of the POC tests were to verify the separation efficiency achieved in the bench-scale tests, achieve similar froth loading capacities, and reduce reagent consumption (i.e., lower operating costs). A three-phase test program was adopted to implement these objectives, consisting of:

- Single-stage tests for the Jameson and packed column cells
- Two-stage tests where the Jameson tailings are recleaned in the packed column cell
- Demonstration tests over extended periods.

First, tests were conducted to establish single cell operations at initial flow rates as determined from the bench-scale tests and recommended by the equipment suppliers. These were followed by tests at increased feed flow rates to determine the limiting capacities for both the Jameson and the packed column cells. In addition, the Jameson cell was also tested with a portion of its tailings stream being recycled to the feed. This had the effect of diluting the feed and improving recovery.

Demonstration tests were conducted in two series, with the first being used to verify the results of previous tests using a longer operational time. Sampling was conducted over 4-hour periods vs. 15-30 minutes for the previous test work. The second series of demonstration tests was used to evaluate steady-state performance of the two-stage circuit over an extended period of time, again using a 4-hour sampling time period. For purposes of comparison, the conventional plant flotation circuit was sampled daily during the demonstration tests.

11.1 POC Test Conditions

The range of test parameters used in POC operations is listed in Table 75 for each circuit. Frother and fuel oil were added as volumetric concentrations and then converted to a kg/t basis after measurement of feed solids concentrations. Frother is also shown as a concentration (ppm).

The single-stage Jameson cell test conditions were selected to achieve high recovery with low product ash. In the case of single-stage operation for this cell with 40% tailings recycle, a slightly higher range of wash water flow rates and deeper froth bed were used (as compared with the first-stage operations discussed below) to adjust for the higher ash content in the downcomer feed. Reagent dosages are given on a raw coal tonne feed basis. The method of wash water addition evolved as the project progressed, as discussed in the next section.

11.1.1 Wash Water Addition

Initial froth recovery problems were encountered with the Jameson cell. Attempts to run at low froth concentrations (<12-15 ppm) led to partial stagnation of the froth and poor discharge. This problem was exacerbated at high fuel oil dosages. The froth stagnation developed within 10 minutes of the start of operations. It was also observed that the water sprays broke up the stagnate froth and restored fluidity only for a short time.

After experimenting with several spray water systems, a wash water tray was installed and used in conjunction with the submerged wash water bars. Approximately 20% of the total wash water was added to the wash water trays. The goal of partial water addition to the trays was to “lubricate” the froth and replace water that drains during froth transport to the discharge lip, thus addressing the problem that led to froth stagnation. Higher additions of wash water to the trays was observed to break down the froth but also inhibit froth migration to the froth lip. This approach proved to be very successful and was used for all subsequent development test work.

Wash water addition to the packed column was also investigated for a different reason. The air flow rate in the packed column cell is higher than that for conventional column cells (3-6 vs. 1.5-2.5 cm/s). The packing and high air flows in the column apparently slow the rate of water drainage from the froth. It was noted early in the test program that conditions that led to a thickened froth resulted in a low ash product. This condition was first achieved by utilization of relatively high levels of fuel oil and frother. Later, wash water addition was modified to create a drainage zone before discharge. Test work, primarily for the second-stage application, determined that in addition to drainage there must be sufficient wash water contact with the rising drainage froth (separation zone) for good separation, i.e., the wash water cannot be only injected deep into the froth bed. The demonstration tests utilized a distributed wash water injection method with 45 cm of drainage and three injection ports at 45, 90, and 135 cm below the froth bed discharge level.

11.1.2 Limits of Equipment Operation

In determining the optimal operation of a two-stage circuit, it was necessary to establish the limits to each machine's operations. The feed volumetric flow rate was increased until the Jameson cell entered the transition from a bubbly flow regime (small discrete bubbles) to "burping" or the consolidation of bubbles. The packed column cell was concurrently operated to assess the effects of changes in feed rate and other parameters on performance.

11.1.3 Jameson Cell Downcomer

The downcomer relies on a venturi effect to draw air into the slurry below an orifice located at the top of the downcomer pipe. At a constant slurry flow rate, air flow is inversely proportional to the vacuum setting. Thus, an increase in vacuum raises the water column in the downcomer and decreases the amount of air drawn into the downcomer. Initial feed rate tests were conducted at 2.6 cm/s and were progressed to 3.8 and 4.5 cm/s. Increasing the feed flow rate through the downcomer led to an increase in the air flow rate at the same downcomer vacuum setting. However, operation at frother levels below 10 ppm led to the formation of slugs or large bubbles rising up through the froth phase (also called "burping") at the higher flow rates. The major factors observed to lead to the onset of slug flow regime are listed below:

- High feed rates
- High solids loadings
- High oil fuel dosage
- High air flow rates
- Low frother dosage

A general observation is that any "hydrophobic" substance such as air, fuel oil or coal increases the likelihood of slug flow. It should be noted that a quasi-steady-state operation was observed during the transition from bubbly flow to slug flow. The cell could be operated in a stable manner at conditions leading to slugs of air rising at 15 or 30 second intervals with no apparent impact on the froth. Despite this steady-state operation, a decision was made not to operate in the transition between regimes and operation in transition was not tested. Stable cell operation with a feed rate of 4.5 cm/s using frother concentrations as low as 6 ppm (0.15 kg/t) was achieved by:

- Operating at a vacuum level of at least 216 cm water
- Restricting air flow rates below 2 cm/s, and
- Keeping fuel oil levels below approximately 0.35 kg/t).

Table 75. Range of Test Parameters Used During POC Operations

Test Parameter	Single-Stage Jameson Cell	Single-Stage Packed Column	First-Stage Jameson Cell	Second-Stage Packed Column
Feed Flow Rate, cm/s				
New Feed	2.6	3.7 & 5.2	2.6, 3.8 & 4.5	3.7, 5.4 & 6.4
Total incl. Recycle*	4.5			
Fuel Oil, kg/t	0.17-0.37	0.15-0.95	0.11-0.76	-
Frother, kg/t	0.19-0.50	0.17-0.76	0.15-0.76	-
Frother, ppm	7-14	7-21	4.8-16.5	
Froth Depth, cm	38-46	165-368	25-46	264-419
Air Flow, cm/s	1.7-2.3	2.6-8.2	1.3-2.2	1.3-5.3
Wash Water, cm/s	0.34-0.47	0.26-0.52	0.25-0.5	0.16-0.6

Note: For single-stage Jameson cell tests, approximately 40% of the tailings was recycled.

Second-stage packed column conditions were chosen to achieve high recoveries with product ash sufficiently low to result in a low combined two-stage product ash. Also, the range in air flow was reduced and the range of froth depth increased to improve separation efficiency to process the high-ash Jameson cell rejects.

For the single-stage operation, different wash water injections were also tested.

11.2 POC Test Results Jameson Cell Wash Water

Partial addition of wash water using a tray mounted above the froth (froth sprinkling) was visually noted to improve froth flow across the cell. The effect of froth sprinkling is highlighted in Table 76 which compares selected tests with similar test conditions but with and without froth sprinkling. The effect is to improve coal matter recovery and maintain product grade. It was also observed to enable cell operation at low frother dosages in which virtually no discharge of froth occurred in the case of 100% submerged froth wash water injection.

Table 76. Effect of Froth Sprinkling, Jameson Cell

Test Parameter	Test Number		
	23	63	129
Froth Sprinkle	No	Yes	Yes
Feed Solids, kg/min	5.3	6.4	8.5
Feed Flow, l/min	160	160	230
Fuel Oil, kg/t	0.23	0.29	0.22
Frother, kg/t	0.32	0.25	0.35
Froth Depth, cm	30	36	30
Air Flow, l/sec	2.2	1.6	2.0
Wash Water, l/min	26	19	25
Feed Ash, %	38	44	33
CC Ash, %	5.7	5	5.4
Refuse Ash, %	52	73	69
CMR,%	66	72	79

11.2.1 Jameson Cell Single-Stage Tests

For initial work to establish single-stage Jameson cell performance, essentially the same conditions were used as for the two-stage tests but with somewhat higher reagent dosages to obtain high recovery. After preliminary operations, it was noted that cell performance improved when the feed solids were more dilute. Discussions with Jameson cell representatives led to the adoption of a tailings recycle operation for the single-stage tests. In this mode of operation, 40% of the Jameson cell refuse stream was recycled back to the feed to dilute the feed solids content and provide another opportunity to capture the lost coal in the recycled stream. (Note that with this approach the effective feed ash to the downcomer also increases.) Tests were run with a new coal slurry feed rate of 160 l/min (2.6 cm/s) and a recycle feed rate of 100 l/min for a total feed rate of 260 l/min. Average conditions for the other process parameters were an air flow rate of 2.0 cm/s, wash water rate of 0.45 cm/s (25% to the wash water tray), and a froth depth of 38 cm. The results of these tests are presented in Figure 32. At a frother dosage of 0.4 kg/t, the coal matter recovery (CMR) using 40% recycle was approximately 85% at a product ash content of 6.0%. These data compare favorably with earlier tests (80% CMR at 5.5% product ash) in which no tailings recycling was used.

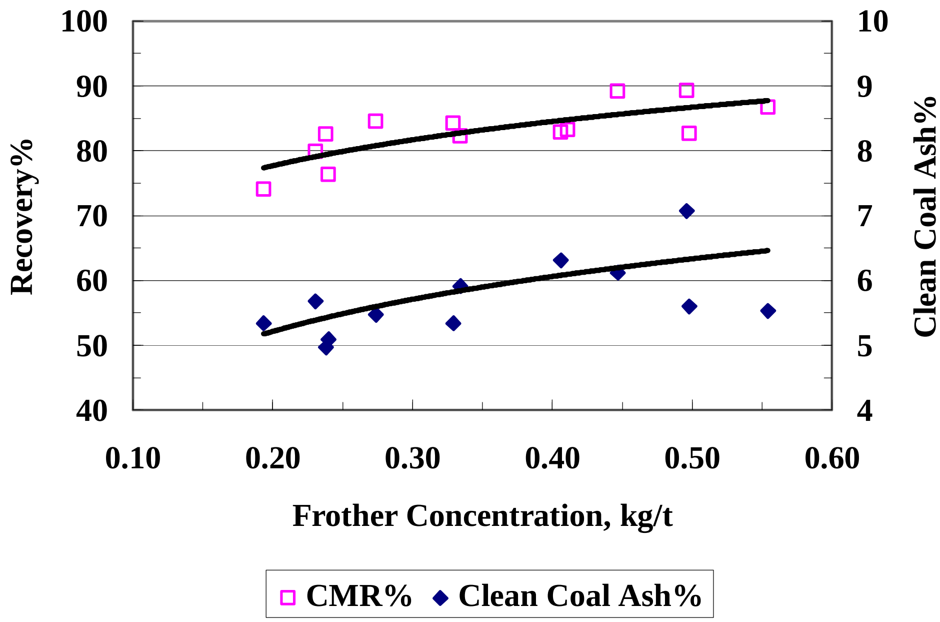

Figure 32. Single-Stage Jameson Cell Performance, 40% Recycle

11.2.2 Packed Column Cell Single-Stage Tests

The emphasis of the packed column test work was on reducing reagent usage while still achieving good separation. Reagent dosage levels used in the bench-scale test work were used as the starting point for POC testing. It was found that by proper adjustment of the froth level, air flow rate, and wash water addition, relatively low reagent dosages could be used, as shown in Table 77. As indicated in this table, reductions in fuel oil could be compensated for by lowering the air flow and increasing the froth depth. This relationship is attributed to the effect of oil on the structure and viscosity of the froth.

Table 77. Packed Column: Reagent Dosage vs. Equipment Parameters

Test No.	Fuel Oil kg/t	Frother kg/t	FO/ Frother kg/kg	Froth Depth cm	Wash Water cm/s	Air STP cm/s	Clean Coal Ash, %	Clean Coal CMR,%
33	1.27	0.69	1.84	201	0.35	5.9	5.8	86.0
35	1.08	0.59	1.84	272	0.30	7.4	7.3	74.7
36	0.95	0.71	1.33	272	0.30	7.4	8.4	88.0
51	0.73	0.32	2.30	272	0.30	6.5	6.9	84.0
50	0.74	0.32	2.30	272	0.30	5.6	8.6	86.2
49	0.69	0.30	2.30	318	0.30	5.4	6.8	65.0
52	0.56	0.26	2.16	272	0.30	6.5	6.8	87.6
53	0.66	0.31	2.16	244	0.30	6.6	6.2	87.2
54	0.69	0.32	2.16	213	0.30	6.8	7.9	82.2
55	0.66	0.31	2.16	213	0.26	6.8	5.8	66.6
154	0.28	0.20	1.38	264	0.35	5.8	7.5	86.1
153	0.42	0.30	1.38	356	0.35	5.9	6.1	85.5
45	0.34	0.22	1.50	318	0.30	5.4	6.0	85.8
149	0.24	0.33	0.72	356	0.43	3.9	7.5	82.5
148	0.15	0.19	0.77	356	0.43	3.9	7.6	82.0

The importance of froth drainage when using lower fuel oil dosages is illustrated in Table 78. The incorporation of a drainage zone at the top of the cell led to large reductions in the clean coal ash content from a range of 13-16% to a range of 6.0-7.5% at the same recovery (85%). The drainage zone enabled operation of the cell at a lower froth depth and slightly less air flow.

Table 78. Single-Stage Packed Column Cell: Froth Drainage for Low Oil Tests

Test No.	Fuel Oil kg/t	Frother kg/t	FO/ Froth kg/kg	Feed Ash, %	Froth Depth cm	Wash Water cm/sec	Sep. Zone cm	Drain. Zone cm	Air STP cm/sec	Clean Coal Ash, %	Refuse Ash, %	CMR %
Tests with no froth drainage												
40	0.45	0.39	1.15	48	348	0.30	348	0	6.2	11.3	76	74.1
41	0.41	0.36	1.15	43	295	0.30	295	0	5.5	13.2	81	85.1
42	0.31	0.27	1.15	45	345	0.30	345	0	5.3	16.8	82	85.9
43	0.35	0.23	1.50	33	345	0.30	345	0	5.3	14.1	88	95.2
Avg	**0.38**	**0.31**	**1.24**	**42**	**333**	**0.30**	**333**	**0**	**5.6**	**13.8**	**82**	**85.1**
Tests with froth drainage												
137	0.30	0.40	0.75	34	264	0.43	148	117	4.1	6.4	84	91.2
148	0.15	0.19	0.77	25	356	0.43	253	103	3.9	7.6	61	82.0
149	0.24	0.33	0.72	26	356	0.43	267	89	3.9	7.5	63	82.5
153	0.42	0.30	1.38	30	356	0.35	288	68	5.9	6.1	72	85.5
154	0.28	0.20	1.38	35	264	0.35	196	68	5.8	7.5	77	86.1
155	0.16	0.17	0.96	30	264	0.43	173	91	4.4	9.4	65	81.5
166	0.27	0.29	0.91	32	264	0.43	192	73	5.8	6.0	74	84.8
Avg.	**0.26**	**0.27**	**0.98**	**31**	**303**	**0.41**	**216**	**87**	**4.8**	**7.2**	**71**	**84.8**

11.2.3 Jameson Cell First-Stage Tests

A wide range of feed rates was used in testing the application of this cell as a first-stage unit. The goal was to determine its suitability for producing low-ash products at high capacities even at lower recoveries. Feed rates ranging from 2.6 to 4.5 cm/sec were used.

Performance at the high flow rates were comparable with that achieved at the lower feed rates, as indicated in Table 79. The high flow rate tests were completed when the plant feed coal ash was lower (34% vs. 43%) and the frother dosage was slightly higher on a kg/t of raw coal basis but similar on a kg/t of coal matter (CM) basis. The average recovery for the high-capacity tests was in fact higher at 77% vs. 68%. This can be attributed, in part, to improved wash water application. The results show that this cell is eminently suitable for a first-stage application at high feed rates.

Table 79. Jameson Cell First Stage Performance, Comparison of Feed Flow Rates

Average Test Parameter	Feed Rate 160 l/min (2.6 cm/s)	Feed Rate 275 l/min (4.5 cm/s)
Number of Tests	13	22
Feed Ash, %	43.0	34
Frother, kg/t	0.30	0.35
Frother, kg/t CM	0.52	0.53
Fuel Oil, kg/t	0.4	0.23
Air Flow, cm/s	1.8	1.9
Wash Water, cm/s	0.31	0.42
Froth Depth, cm	33.0	40
Clean Coal Ash, %	5.2	5.6
Refuse Ash, %	69.0	66
CMR %	67.5	76.7

All tests with frother dosage >0.2 kg/t and <0.45 kg/t.

11.2.4 Packed Column Cell Second-Stage Operation

The tailings from the Jameson cell were recleaned in the packed column. In this case also, the cell operation was determined to be sensitive to the same process variables as in the single-stage operation. High fuel oil dosages required high air flows to get combined circuit recoveries above 80%. Reducing the fuel oil and frother with lower air flow was found to still achieve good recovery. A summary of the second-stage performance in shown in Figure 33 for tests with the following conditions:

- Frother dosage <0.6 kg/t
- Fuel oil dosage <0.8 kg/t
- Froth separation depth >200 cm
- Froth drainage depth <130 cm

The froth ash content was found to be correlated to the second-stage feed ash content. It is important to note that the latter is itself related to the initial frother dosage which was found to be the major process variable affecting first-stage performance.

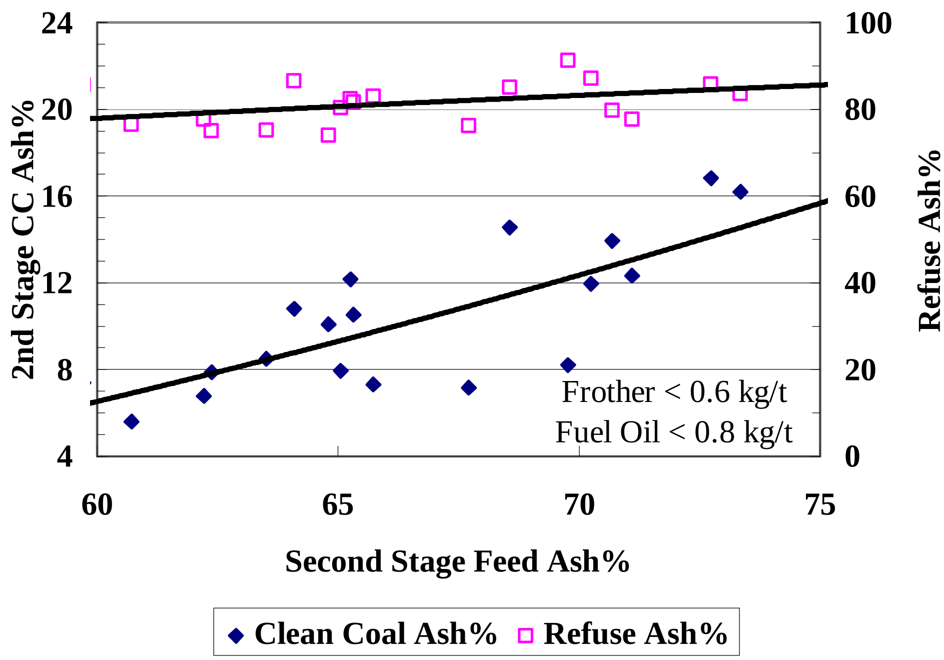

Figure 33. Packed Column Second-Stage Performance: Low Reagent Tests

Comparison of the test data by feed flow rate indicates that cell performance is only marginally reduced by changes in the flow rate (see Table 80). The average test condition also illustrate how the test work progressed towards lower reagent dosages, especially fuel oil. The high flow rate tests required a reduction in fuel oil dosage for proper downcomer operation, as previously discussed.

Table 80. Packed Column Second-Stage Performance: Low and High Flow Rate Averages

Average Test Parameter	Feed Rate 160 l/min (3.7 cm/s)	Feed Rate 275 l/min (6.3 cm/s)
Feed Ash, %	70.0	67.2
Fuel Oil, kg/t	0.39	0.32
Frother, kg/t	0.28	0.33
Air Flow, cm/s	3.4	2.3
Wash Water, cm/s	0.26	0.4
Froth Depth, cm	370	358
CC Ash, %	12.6	11.4
Refuse Ash, %	85.8	82.3
CMR %	61.1	56.6

The trends of the second-stage test results are summarized with respect to feed ash in Table 81 to better clarify flow rate comparisons. Second-stage recovery is shown to drop with increasing feed ash for all flow rates. The results indicate that lower flow rates result in slightly higher second-stage recovery (63.5% vs. 56.5%).

Table 81. Packed Column Second-Stage Performance: Trend Line Data Summary

Feed Ash, %	Clean Coal Ash, %	Refuse Ash, %	Second-Stage CMR , %
Feed Rate: 3.7 & 4.9 cm/s			
60	6	80	63.5
65	9	81	57.8
70	12	82	50.3
Feed Rate: 6 cm/s			
60	7	77	56.5
65	11	80	55.3
70	n/a	n/a	
Feed Rate: 6 cm/s, deep wash water injection			
65	20	80	57.1

Feed solids >1% solids
Initial frother concentration <0.6 kg/t or <15 ppm

Table 81 also illustrates the effect of adding wash water too deep into the froth zone. When most of the wash water was injected at a depth of 135 cm, it resulted in a significant increase in product ash in the range of 15% to 28% in spite of the froth thickening achieved by the large froth drainage zone.

11.2.5 Combined Two-Stage Performance

Efficient operation of the two-stage circuit required compatibility between each stage with respect to selection of operating conditions. The primary parameter that required optimization was fuel oil dosage. Higher levels of fuel oil were favorable for packed column operation in that lower froth bed depths could be used and a consistent low ash product could be produced, although this required higher air flows. However, high levels of fuel oil were detrimental to Jameson cell downcomer performance at high flow rates, as previously noted. Test work indicated that if the fuel oil dosage was kept in the range of 0.2 to 0.4 kg/t, high recoveries from the first stage would be realized and good two-stage performance could be achieved.

Figure 34 presents the results of the two-stage circuit performance when the proper operating conditions are utilized.

The criteria for selection of tests presented in Figure 34 are:

- Fuel oil dosage 0.2 to 0.4 kg/t
- Frother dosage 0.2 to 0.6 kg/t
- Jameson cell froth depth >25 cm
- Packed column separation froth depth >200 cm
- Packed column cell drainage froth depth <130 cm
- Packed column air flow <4 cm/s

The results were found to correlate best with feed ash as presented in Figure 34, for both low (160 l/min or 2.6 cm/s) and high (275 l/min or 4.5 cm/s) feed rates. The two-stage circuit consistently achieved recoveries above 80%, with an average of 89% for these conditions. The average recovery from the first stage was 74% and the average second-stage recovery was 56%. In general, the feed ash during the low flow rate tests was higher than during the subsequent high flow rate tests. The feed rate ash had little impact on the overall recovery of the system, but did cause a slight increase in the product ash content. The data trend indicate that with a feed ash below 30%, the clean coal ash would be 5.5%, increasing to 7% for a feed ash of approximately 45%.

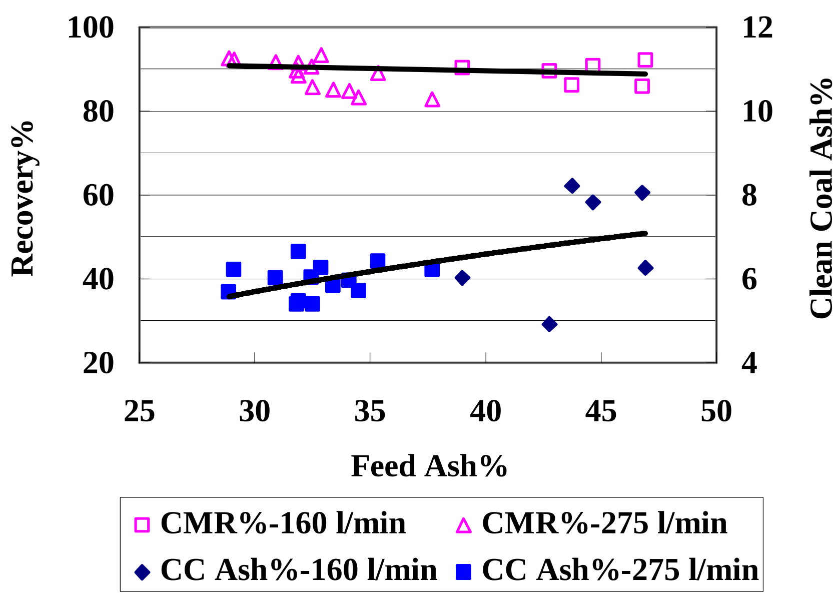

Figure 34. Two-Stage Combined Performance: Development Tests

12.0 DEMONSTRATION TESTS

Following completion of the development test work, a series of demonstration tests was performed. The demonstration tests were completed in two one-week periods. During the first week, the plant was operating normally and in a stable mode. During the second test period, there was a major shift in coal quality and the plant recoveries in the flotation cells dropped significantly. The samples collected from the existing plant flotation circuit shown in series of demonstration tests.

Table 82 confirm that the feed coal quality was dramatically different between the first and second test periods. For the first demonstration period, recovery was 79.5%, which agrees with historical data. In the second period, the recovery was only 43%. A review of detailed historical plant flotation data indicates that poor flotation results were observed in about 1 in 25 collected daily samples. These poor coal flotation characteristics lasted during the entire second series of demonstration tests.

Table 82. Plant Flotation Cell Performance During Demonstration Tests

Sample Date	Solids Wt. %	Frother* kg/t	Feed Ash %	CC Ash %	Refuse Ash %	Yield %	CMR %
11/21/96	3.2	0.18	37.0	10.1	70.7	55.7	79.4
11/22/96	2.8	0.20	35.4	10.6	68.8	57.3	79.3
11/27/96	3.1	0.19	37.1	11.0	71.8	57.0	80.7
12/02/96	4.5	0.13	40.9	12.8	72.4	52.9	78.0
12/05/96	3.8	0.16	37.8	11.8	71.7	56.6	80.2
12/11/96	3.9	0.15	39.8	11.1	73.0	53.6	79.2
Average	3.5	0.17	38.0	11.2	71.4	55.5	79.5
12/12/96	2.7	0.21	37.5	10.3	48.8	29.3	42.1
12/13/96	3.6	0.16	41.2	13.1	54.3	31.8	47.0
12/14/96	3.6	0.16	41.1	10.1	47.5	17.3	26.3
12/16/96	3.6	0.16	37.9	8.1	50.5	29.6	43.8
12/18/96	3.5	0.17	32.9	7.4	50.1	40.4	55.7
Average	3.4	0.17	38.1	9.8	50.2	29.7	43.0

* Fuel oil dosage was 0.3-0.35 kg/t.

The major emphasis of the demonstration tests was to evaluate the merits of long-term two-stage circuit operation. The major process variables tested were frother and fuel oil dosage, with only minor adjustments being made to equipment parameters settings as determined in the development work. A limited number of single-stage tests was conducted to verify the results of the previous work.

12.1 Single-Stage Demonstration Tests

During the first series of tests, 8 Jameson cell and 8 packed column single-stage tests were completed. The results of these tests were similar to those obtained previously and were combined with the early test work, as previously reported.

In the second series of tests, only one single-stage test was completed for each cell. The Jameson cell test with recycle resulted in a product ash of 7.5% and recovery of 82%. The packed column cell test resulted in a recovery of 74% at 11% product ash. These results indicate a drop in recovery and increase in clean coal ash for this coal.

12.2 Two-Stage Demonstration Tests

The key emphasis of the demonstration tests was on evaluating long-term two-stage circuit operations. The major process variables tested were frother and fuel oil dosage, with only minor adjustments being made to equipment parameter settings as determined in the previous development work.

Eight tests were conducted during the first series of demonstrations using a lower reagent dosage (frother = 0.15 to 0.2 kg/t). The remaining 24 tests were completed in the second series using a frother dosage of 0.2-0.4 kg/t.

The results of the two-stage tests are given in Figure 35 through Figure 38. Combined two-stage coal recovery ranged from 70% at 0.15 kg/t frother to 90% at 0.3 kg/t frother. Recovery for each stage ranged from approximately 50 to 75% for the first-stage Jameson cell and 40 to 60% for the second-stage packed column cell, which is approximately 2-5% below recoveries measured previously. In addition, the clean coal ash content was higher for both the Jameson cell and packed column cell. For instance, the Jameson cell product ash ranged from 6 to 8% compared with 5-6.5% ash measured previously for similar test conditions. The packed column second-stage clean coal ash increased from 10% to 13% ash at a feed ash of 65%.

The second-stage performance results are more consistent when test results are trended with respect to feed ash, as shown in Figure 38. For the second-stage feed ash of 65%, the clean coal ash content ranged from 11 to 15%, with a refuse ash of approximately 80%.

In general, the demonstration tests confirm that good flotation performance can be achieved using the two-stage circuit approach. Stable operations were achieved during pilot plant operations lasting 17 shifts, especially when compared with the plant flotation circuit operation. The two-stage circuit recovery was consistently higher than 80% for frother dosages greater than 0.2 kg/t.

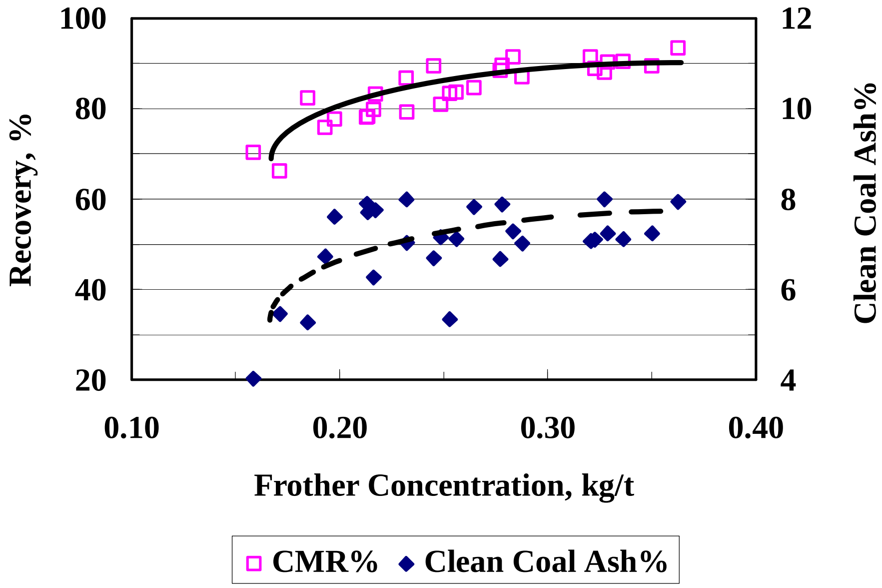

Figure 35. Two-Stage Circuit Combined Performance: Demonstration Tests

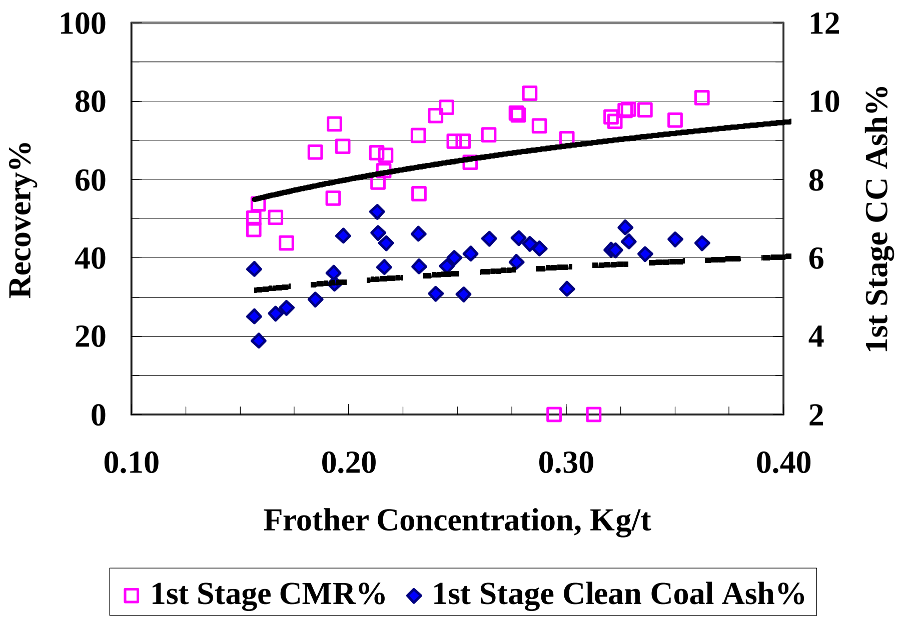

Figure 36. First-Stage Jameson Cell Performance: Demonstration Tests

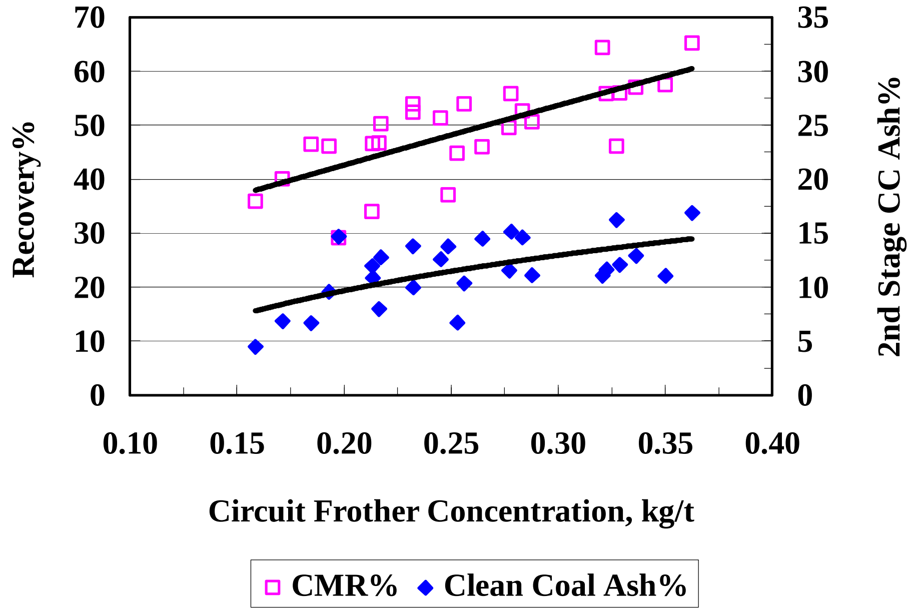

Figure 37. Second-Stage Packed Column Cell Performance: Demonstration Tests

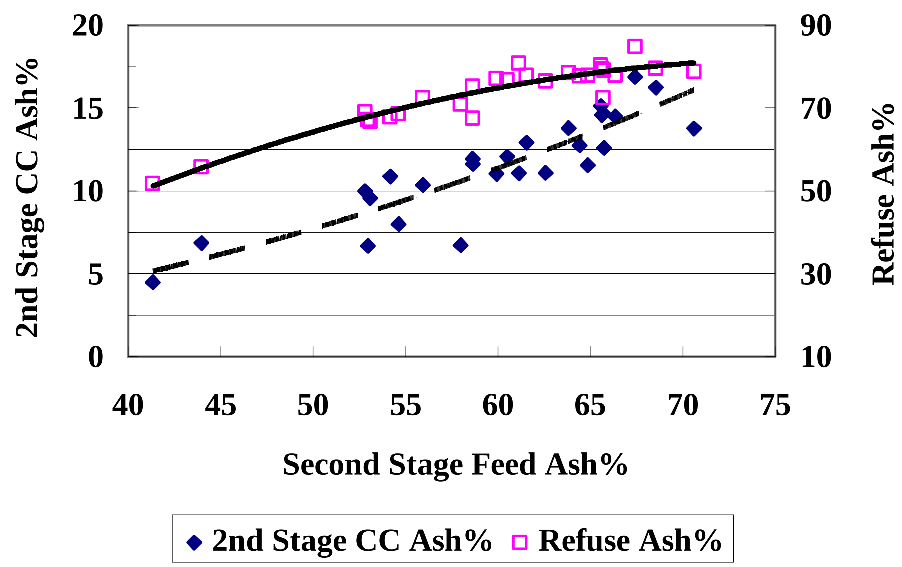

Figure 38. Second-Stage Performance vs. Feed Ash: Demonstration Tests

13.0 CONCLUSIONS AND RECOMMENDATIONS

13.1 Bench-Scale Testing and Evaluation

In Phase I, four advanced flotation cells, i.e., a Jameson cell, an Outokumpu HG tank cell, an open column, and a packed column, were subjected to bench-scale testing and demonstration.

The bench-scale test results for the Jameson cell demonstrated that at 85% energy recovery, ash and sulfur rejections are 85% and 30% respectively. Tests also showed that the grade/recovery curve for the Pittsburgh seam coal feed is very steep, i.e., a large increase in recovery can be realized with only a small increase in the product ash content. This is indicative of a high degree of liberation.

The bench-scale test results for the Outokumpu cell did not achieve recoveries of 85% or higher, and its ash and sulfur rejections were correspondingly lower for the same feed.

The bench-scale test results for the packed column operated as a single-stage operation achieved the ash target of 5.0% for all tests except one, and at least half of the tests also provided energy recoveries higher than 85%. Subsequently, the packed column was operated at mass loadings 33% higher than the previous tests (feed of 3.34 tph/m^2 or 5.4 gm/min/cm^2) and still achieved good process efficiency. The results of these tests show that a high energy recovery of 87% was achieved at a product ash content of 4.9%. Also, total sulfur rejection of about 35% was obtained at energy recoveries of 85%. For the packed column used as a second-stage flotation cell, tests were conducted on a tailings sample at 1.4% solids with a feed velocity of 3 cm/s, which corresponds to a 2-minute residence time. At these conditions, the tailings ash content was about 75% with a corresponding energy recovery of 74-76%. The clean coal ash content ranged between 6.5 and 10% with froth loadings of up to 0.68 tph/m^2, indicating good separation efficiency for second-stage operation.

Tests conducted with the open column using raw coal fines achieved a clean coal ash content in the range of 8-9%, and energy recovery was approximately 78% using an aeration rate of 1.8 cm/s and 88% for an aeration rate of 2.5 cm/s. Tests conducted with the tailings feed (simulated second-stage operation) demonstrated that an 8-9% ash product could be recovered from processing the high-ash tailings, with energy recovery in the range of 80 to 85% at feed rates of up to 1.84 cm/s.

After reviewing the performance data and related economics, the following flotation machines and circuits were recommended for pilot testing:

- Single-stage Jameson cell
- Single-stage packed column
- First-stage Jameson cell, second-stage packed column.

The Jameson cell was selected for the first stage based on its good performance and low operating costs (it does not require compressed air). It demonstrated the potential for application as a first-stage machine by achieving the highest froth mass loading levels measured while producing a 4% ash product.

In general, the performance of both the open and packed columns was very good. However, the packed column demonstrated a higher capacity with the raw coal feed with corresponding higher froth mass loadings. The packed column was selected in favor of the open column because of its:

- Potential for achieving high froth mass loading levels
- Potential for process control via regulation of froth depth
- Enhanced process separation efficiency when producing a low-ash product.

13.2 Pilot-Scale Testing and Operation

A two-stage proof-of-concept (POC) flotation circuit using the Jameson cell in the first stage and the packed column cell in the second stage was constructed at the coal preparation plant. The design also allowed for operation of each cell as a standalone unit (single cell operation). First, tests were conducted to establish single cell operations at initial flow rates as determined from the bench-scale tests and recommended by the equipment suppliers. This was followed by tests at increased feed flow rates to determine the limiting capacities for both the Jameson and packed column cells. In addition, the Jameson cell was tested with a portion of its tailings stream being recycled to the feed. This had the effect of diluting the feed and improving recovery.

The range of test parameters used in POC operations was similar to those established during laboratory testing but was scaled up. The single-stage Jameson cell test conditions were selected to achieve high recovery with low product ash. In the case of single-stage operation with 40% tailings recycle, a slightly higher range of wash water flow rates and deeper froth bed were used than for first-stage operation to adjust for the higher ash content in the downcomer feed. The conditions selected for single-stage packed column cell operation were based on the same objectives of high recovery and low product.

13.3 Comparison of Pilot Plant and Bench-Scale Results

In general the pilot plant tests achieved similar performance to the bench-scale test work with the added improvement of reduced operating costs. A comparison of bench and pilot plant operations at near-optimal operating conditions is given in Table 83. Optimization of the Jameson cell operations resulted in lower fuel oil and frother requirements which enable operation at maximum air flow rates. As a consequence of improved Jameson cell operations, higher coal recoveries were achieved in the first stage (77% vs. 73% for bench-scale testing). In the case of the packed column cell, lower reagent dosages and reduced coal loadings (higher feed ash) led to a reduction in air flow rates and the use of deeper froth bed depths than those projected by scale-up. Differences in coal matter recovery and product and refuse ash levels for the two-stage work can be attributed to the high feed flow rates tested for the packed column cell (6.3 cm/s for the pilot tests vs. 3 cm/s for the bench-scale tests), relatively high frother dosages used in the bench-scale tests, and differences in the feed coal ash content. The feed coal samples used in the bench-scale tests had an ash content of 20-23% whereas those used in the pilot plant work had an ash content in the 30-43% range. This would contribute to the slightly higher product and tailings ash content measured for the pilot plant tests.

Table 83. Comparison of Bench-Scale to Pilot-Scale Tests

	Bench-Scale Tests (Feed Coal Ash 23.0%)				Pilot-Scale Tests(1) (Feed Coal Ash 30-43%)			
	Single-Stage		Two-Stage		Single-Stage		Two-Stage	
Process Parameter	Jameson	PC	Jameson	PC(2)	Jameson	PC	Jameson	PC
Feed Velocity, cm/s	1.10	3.00	4.57	2.97	2.7	3.6	4.5	6.3
Fuel Oil Dosage, kg/t	1.34	0.93	1.0	1.4	0.28	0.43	0.23	None
Frother Dosage, kg/t	0.67	0.46	0.38	0.7	0.42	0.27	0.35	None
Aeration Rate, cm/s	NA	4.2	NA	4.2	2.0	4.2	1.9	2.3
Wash Water Velocity, cm/s	0.17	0.28	0.78	0.28	0.38	0.35	0.42	0.4
Froth Mass Loading, gm/min/cm2	1.25	4.0	4.5	1.5	3.7	4.1	6.7	0.93
Product Ash, %	4.70	4.90	3.80	6.5	6.1	6.8	5.6	11.4
Refuse Ash, %	61.0	60.0	45.0	75.0	76.0	75.0	66.0	82.0
Energy Recovery, CMR, %	85.4	87.2	72.9	73.9	85.0	84.8	76.7	56.6
Total Circuit CMR, %	85.4	87.2	--	92.9	85.0	84.8	--	89.9

(1) Optimal non-demonstration pilot plant tests.
(2) Simulated second-stage circuit performance using existing plant tailings sample

13.4 Pilot Plant Demonstration Tests

In general, the demonstration tests confirm that good flotation performance can be achieved using the two-stage circuit approach. Stable operations were achieved during pilot plant operations lasting 17 shifts, especially when compared with the plant flotation circuit operation.

Combined two-stage coal recovery ranged from 70% at 0.15 kg/t frother to 90% at 0.3 kg/t frother. Recovery ranged from approximately 50% to 80% for the first-stage Jameson cell and 40-60% for the second-stage packed column cell, which is approximately 2-5% below recoveries measured previously. In addition, the clean coal ash content was higher for both the Jameson cell and packed column cell. For instance, the product ash for the Jameson cell ranged from 6 to 8% compared with 5-6.5% measured previously for similar test conditions. The packed column second-stage clean coal ash increased from 10 to 13% ash at a feed ash of 65%. This change in performance may be attributed to a change in the coal feed properties, which is borne out by the fact that the existing plant flotation circuit performance revealed a much more severe drop in recovery (79.5% to 43.0%).

13.5 Process Operation Recommendations

This section summarizes the feed criteria and provides recommendations for circuit configurations and the range of process parameters required for optimal performance.

The coal used for this work was Pittsburgh seam with the following properties:

- Particle size: 80% minus 150 microns
- Ash content: 25-45% for raw coal, second-stage ash content 50-65%
- Solids content: 2.5-4.0%

The two-stage circuit was shown to achieve higher energy recovery than both single-stage circuits when compared at equivalent reagent dosages. Optimization of reagents was important in achieving good pilot plant operations. Lowering the fuel oil dosage enabled the Jameson cell to operate at higher flow rates with lower frother requirements. The packed column cell was also able to operate at lower reagent dosages by increasing the froth bed depth and reducing air flow rates.

The recommended conditions for operating the pilot plant two-stage circuit are:

- Fuel oil dosage: 0.25 to 0.35 kg/t
- Frother dosage: 0.25 to 0.3 kg/t
- Jameson cell froth depth: >25 cm
- Jameson air flow rate: 2 cm/s
- Jameson wash water flow rate: >0.4 cm/s
- Packed column froth depth: >300 cm (assuming 7 m tall column)
- Packed column air flow rate: <4 cm/s
- Packed column wash water flow rate: >0.4 cm/s

13.6 Recommendations for Further Work

Operation of the single-stage Jameson cell established that recycling up to 40% of the tailings to the cell feed had little impact on its performance in terms of product quality, and improved recovery by 5%. It would be worthwhile to test this approach with the two-stage circuit. The concept of recycling could be applied to the two-stage circuit by recycling the packed column cell product back to the Jameson cell feed instead of adding it to the clean coal stream. The packed column cell could then be operated for high recovery by increasing air flow rates and/or reducing froth depths. The recycled packed column froth would have a lower ash content and more coal than the 40% Jameson cell tailings recycle, especially if the packed column cell was operated to produce a product ash of 20-30% (vs. 10-15% ash when the second-stage froth reports to the clean coal, as in the pilot plant configuration). If the recycle stream were added to the new feed before adding reagents (as was the case with the Jameson cell tailings recycle), the new reagent addition would improve the flotation kinetics of the recycled froth. Any remaining frother in this stream would also improve Jameson cell operations. With 100% of the product coming from the Jameson cell, this circuit could be expected to be very stable with respect to the product ash content provided that sufficient wash water was added to maintain a slightly negative or neutral bias with wash water.

The circuit suggested above could be integrated with the two-stage circuit configuration tested in the pilot plant. Using a flow gate to control the direction of the packed column cell froth, the circuit could be configured either to send the second-stage product to the clean coal stream or recycle it back to the Jameson cell feed. This flexible approach would allow operations to adjust the flotation circuit to match feed conditions. During periods when the overall circuit froth mass flow rate is low (lower feed solids contents and/or high feed ash), the circuit could be operated in recycle mode for additional recovery. When high feed solids and/or low feed ash conditions are experienced, the second-stage froth could be diverted to the product to increase the overall circuit froth mass flow output.