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Engineering Development of Advanced Physical Fine Coal Cleaning for Premium Fuel Applications

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ABSTRACT

The goal of this project is engineering development of two advanced physical fine coal cleaning processes, column flotation and selective agglomeration, for premium fuel applications. Its scope includes laboratory research and bench-scale testing on six coals to optimize these processes, followed by design and construction of a 2 t/h process development unit (PDU). Large lots of clean coal are to be produced in the PDU from three project coals. Investigation of the near-term applicability of the two advanced fine coal cleaning processes in an existing coal preparation plant is another goal of the project and is the subject of this report.

A survey of Amax Coal Company properties showed potential applications of the advanced technologies at preparation plants of the Ayrshire and Wabash Mines in the Midwest and at the Lady Dunn Preparation Plant in West Virginia. A column flotation installation at the latter plant was particularly attractive because of an expansion program then in progress. A conceptual evaluation indicated that clean coal centrifuge cake could be produced there for $6.20/st (dry basis) when using column flotation. Thermal drying would add $8.80/st to the cost. The total cost of column flotation, thermal drying and briquetting was projected to be $23.00/st. Selective agglomeration using diesel fuel as the bridging liquid was found to be more expensive.

Subsequently, pilot testing of the advanced flotation technology was conducted at the Lady Dunn Plant using a 30-inch diameter Microcel™ column. The column could process between 40 and 120 gpm of a slurry of natural raw-coal fines containing 40 percent ash. Clean coal containing 10 to 11 percent ash was produced at 75 percent combustible recovery. Operating conditions for good recovery of coarse coal particles (0.25 x 0.50 mm) were identified during the parametric testing. Proper frother dosages were necessary to ensure sufficient bubble surface area for attachment of the coarser particles. Larger bubbles with less surface area formed at low frother dosages, and these bubbles were easily overloaded by the preferential attachment of the finer particles of coal.

In light of the good results achieved with the 30-inch column, Cyprus Amax installed three 4-meter diameter columns during their recent expansion of the Lady Dunn Plant. The columns are performing as expected from the pilot work.

Auxiliary operations for improving the marketability of the clean coal, including vacuum filtration, centrifuging, GranuFlow processing, CWF preparation and briquetting, were also investigated. Good results were achieved by high-pressure binderless roll-press briquetting.

EXECUTIVE SUMMARY

This project is a major step in the Department of Energy's program to show that ultra-clean coal-water slurry fuel (CWF) can be produced from selected coals and that this premium fuel will be a cost-effective replacement for oil and natural gas now fueling some industrial and utility boilers in the United States. The premium CWF could also fuel advanced combustion systems now under development.

The replacement of oil and gas with CWF can only be realized if retrofit costs are kept to a minimum and retrofit boiler emissions meet national goals for clean air. These concerns establish the specifications for maximum ash and sulfur levels in the fuel and the combustion properties of the CWF.

PROJECT OBJECTIVES

The project has three major objectives:

- The primary objective is to develop the design base for prototype commercial advanced fine coal cleaning facilities capable of producing ultra-clean coals suitable for conversion to coal-water slurry fuel for premium fuel applications. The fine coal cleaning technologies are advanced column flotation and selective agglomeration.
- A second objective is to develop the design base for near-term application of the advanced coal cleaning technologies in new or existing coal preparation plants to efficiently process minus 28-mesh coal fines and convert them economically into marketable products.
- A third objective is to determine the removal of toxic trace elements from coal by advanced column flotation and selective agglomeration technologies.

This report summarizes the work done to accomplish the second objective, that is, Task 3 for the development of near-term applications of the advanced fine coal cleaning technologies in existing preparation plants.

PROJECT APPROACH

The project team consists of Cyprus Amax Minerals Company through its subsidiaries Amax Research & Development Center (Amax R&D) and Cyprus Amax Coal Company (Midwest and Cannelton Divisions), Bechtel Corporation, Center for Applied Energy Research (CAER) of the University of Kentucky, Arcanum Corporation, and Center for Coal and Mineral Processing (CCMP) of the Virginia Polytechnic Institute and State University. Entech Global manages the Project for Amax R&D and provides research and development services. Dr. John P. Dooher of Adelphi University and Dr. Douglas V. Keller, Jr. of Syracuse University are consultants to the project.

The overall project effort was divided into four phases which were further divided into eleven tasks, including coal selection, laboratory- and bench-scale process optimization, and design, construction, and operation of a 2 st/hr process development unit (PDU). This investigation of near-term applications of the advanced cleaning technologies to existing coal preparation plants was performed as Task 3 of the project.

TASK 3 OBJECTIVES

As indicated earlier, Task 3 is an extension of the premium fuel project to specifically address the use of advanced flotation and selective agglomeration processes for recovering fine coal lost in existing coal preparation plants. The goal will be to produce a clean coal product which can be sold in existing markets by one or both of the following strategies:

- Increase the percentage recovery of marketable coal from the ROM coal.
- Improve the quality and value of the marketable coal (heating value, sulfur or ash content, and handling characteristics) in a cost-effective manner.

If this goal can be achieved, these applications would represent immediate near-term benefits to be gained from the project and would complement the long-term benefits to be gained from the production of premium fuel from coal.

The task was divided into two subtasks with related objectives. The first of these subtasks, Subtask 3.1 Engineering Analysis, had four objectives:

1. Identify potential applications of the two advanced fine coal cleaning processes in new or existing coal preparation plants.
2. Identify subsystems required to yield a near-term marketable product acceptable to customers.
3. Conduct preliminary assessments of the cost, technical risk and economic viability of one or more near term applications of advanced flotation and/or selective agglomeration.
4. Select an application or applications for engineering development and testing to produce a marketable, shippable product.

The second subtask, Subtask 3.2 Engineering Development, had as its primary objective the pilot-scale testing and engineering development of the selected application or applications. This objective included the engineering development of auxiliary subsystems required for plant integration and production of a marketable, shippable product.

Later, the contract was modified to add Subtask 3.3, Dewatering Studies to be performed by Virginia Tech. A separate report from Virginia Tech will present the results of that study.

TASK 3 APPROACH AND SCOPE

A five-step approach was followed to accomplish the Task 3 objectives. The steps were as follows:

1. Survey, with close cooperation from division-level operating management, Amax Coal Company properties to determine which preparation plants were candidates for application of the new technologies. The factors to be considered included the extent of the fine coal losses in the various plants, the accessibility of the waste coal streams for study, and the likelihood of a major renovation or expansion of the plant.

2. Perform laboratory column flotation and selective agglomeration amenability tests on samples collected from the candidate preparation plants in order to determine operating conditions and potential product quality and recovery.

3. Design conceptual plants integrating the advanced flotation and selective agglomeration technologies into the existing plants and estimate the capital and operating cost for the additional production from the integrated plants. From these data, recommend confirmation testing, if any, to the DOE and the coal company.

4. Confirm laboratory projections by continuous pilot-scale testing of the recommended application at the host preparation plant. Also, further optimize process conditions to obtain design parameters so that the coal company may assess feasibility of a plant conversion to the advanced cleaning process.

5. Determine dewatering, CWF preparation, and briquetting properties of fine clean coal from the pilot operation so that the marketing prospects of the additional coal production can be included in the coal company assessment.

As indicated earlier, accomplishment of the Task 3 objectives was a team effort of Amax Coal Company (later to become part of Cyprus Amax Coal Company), Amax R&D (and later Entech Global), Bechtel, CAER, Arcanum and CCMP. The laboratory testing was done at Amax R&D, CAER, Arcanum and CCMP. Cannelton, a part of Cyprus Amax, was responsible for installation of the pilot-scale equipment at the Lady Dunn Preparation Plant host site, and CCMP operated the equipment and provided the technical direction for the on-site testing. Filtration tests were conducted by Westech, and continuous centrifuge dewatering tests were conducted by DOE/FETC at Pittsburgh. TraDet performed the continuous briquetting tests.

ADVANCED PHYSICAL FINE COAL CLEANING TECHNOLOGIES

The two physical fine-coal cleaning technologies being developed for production of premium fuel are advanced froth flotation (specifically, column flotation) and selective agglomeration.

Column flotation differs from the more common mechanical-cell flotation since the air is injected into a deep tank rather than into a series of shallower mechanically agitated tanks. The dispersion of the air is often thought to be better in the deeper column system because of the manner in which the air is introduced into the slurry. A more important difference between the two types of flotation, though, is the capability of adding rinse water effectively to the top of the column. This water, flowing countercurrent to the clean coal, washes entrained and adventitious non-floating material from the froth and has the same effect as adding multiple stages of cleaner flotation to a mechanical-cell system. Rinse water additions have been found to be particularly helpful when floating coal from high-ash slurry.

Selective agglomeration cleaning is accomplished by coating particles of fine coal with droplets of an oily bridging liquid under a high-shear mixing regime. Continued mixing encourages the oiled particles to stick together and grow into larger pellets which can be separated from the dispersed waste by screening or by froth flotation. The procedure is noteworthy for its efficiency -- the recovery of fine carbonaceous material by selective agglomeration is often better than by froth flotation alone. Various types of bridging liquids can be used, including volatile hydrocarbons which can be recovered for reuse. Because the technology for recycling volatile bridging liquids has not yet been developed beyond the bench scale, only a non-recovery system with diesel fuel, kerosene or heating oil bridging liquid was considered for near-term applications during this project.

POTENTIAL LOCATIONS FOR NEAR-TERM APPLICATIONS

As a first step, team-member Amax Coal Company was asked to suggest candidate locations for application of the new technologies. After considering performance records and plans for future production, the Midwest Division (Illinois and Indiana) technical management recommended that the task focus on the Ayrshire Plant and the Cannelton Division (West Virginia) recommended that the task focus on the Lady Dunn Plant. Sometime later, when it was learned that the Ayrshire Mine would be closing, the Midwest Division asked that the Wabash Plant also be considered as a study site for the near-term application.

Amax R&D and Bechtel engineers visited each of the sites to assess their suitability as host sites for the eventual pilot-scale testing. At the same time, the Amax R&D engineers arranged for collection of fine coal samples for laboratory amenability tests, and Bechtel engineers arranged to obtain the existing plant layout and operating data that they would need for the conceptual-design and economic-feasibility studies.

The specific near-term applications at the three preparation plants are described separately in the following sections.

Ayrshire Preparation Plant

The Ayrshire Mine and Preparation Plant northeast of Evansville produced surface mined coal from the Indiana VI seam. The preparation plant was a 1,200 st/hr jigging operation originally placed into service in 1973. The minus 28-mesh underflow from the clean coal dewatering screens was cycloned, and the cyclone overflow discarded to a slurry pond. The cyclone underflow was dewatered with basket centrifuges and combined with the clean coal from the jig plant. A significant amount of clean coal was lost in the cyclone overflow, and the quality of the overall plant production was degraded by the excessive amounts of moisture and ash retained in the centrifuge cake. Product quality was an important consideration at Ayrshire since low sulfur coals were being purchased at the time to blend with the plant production in order to meet customer specifications.

The main focus of the near-term application was the 80 st/hr (dry basis) of fine refuse going to the slurry pond. It was viewed as a potential source of low sulfur coal which could replace some of the coal being purchased as blending stock. In addition some attention was given to improving the quality of the centrifuge cake, perhaps by including a grinding step ahead of advanced cleaning.

Lady Dunn Preparation Plant

The Lady Dunn Preparation Plant east of Charleston, West Virginia, received Stockton and Eagle seam coal from a nearby underground mine. The plant had a heavy-media vessel/shaking table/mechanical-cell flotation circuit and had a capacity of 550 st/hr when the task began in 1992. A multiphase expansion to 1200 st/hr, involving replacement of the shaking tables with additional heavy-media cyclones and spiral separators was on the planning board at the time.

An initial evaluation of the plant operation indicated that the Lady Dunn plant could benefit from the use of advanced cleaning technology to treat the additional fines that would be generated by the expansion. Since the plant was being expanded anyway, the advanced cleaning units could be easily incorporated into the circuit if found to be beneficial. In addition to the production of a larger quantity and a better quality clean coal for steam coal customers, the advanced technology could also produce low-sulfur special fuels from the coal being mined at that location. Manufacture of coal briquettes as a premium stoker fuel for industrial boilers would be a particularly attractive option. Other options would be the sale of the clean coal as a powder fuel or as CWF for firing industrial boilers in the area.

The overflow stream from the classifying cyclones in the expanded plant was identified as a candidate for treatment by the advanced technology. The overflow was expected to contain 35 tons of dry solids per hour. At the time, plant management envisaged installation of additional mechanical flotation cells to clean this stream. Based upon past experience, they expected to achieve 50 percent recovery, at most, of the combustible material in the cyclone overflow. Vorsiv underflow slurry feeding the existing mechanical-cell flotation circuit was collected for the amenability testing discussed in this report. Since the contemplated feed to the expanded plant also included streams of coarser material than the minus 48-mesh Vorsiv product, a raw coal sample was also collected that could be screened later to make a 28x100-mesh fraction for separate testing.

Wabash Preparation Plant

The Wabash Mine and Preparation Plant near Keensburg, Illinois, produced coal from an underground mine in the Illinois No. 5 seam. The preparation plant was a 1,500-tph heavy-media vessel/heavy-media cyclone operation that had been placed into service a few months earlier. The minus 1-mm fines from the heavy-media cyclone feed were cycloned with the plus 0.15-mm oversize going to spiral separators and the minus 0.15-mm overflow going to the refuse thickener and disposal. It was proposed to clean the latter stream by an advanced technology since coal recovered here would increase the overall production of saleable coal from the mine. Recent test data developed to support an unfunded Clean Coal Technology V submission were available in the coal company files so it was not necessary to obtain new samples from the preparation plant for testing.

LABORATORY AMENABILITY TESTING

Portions of the slurry samples collected at the Ayrshire and Lady Dunn Plants were distributed to Amax R&D, CAER, and Arcanum for the initial amenability testing. A second sample of the Lady Dunn flotation feed slurry was collected at a later date and tested at CCMP to confirm the earlier observations at Amax R&D and CAER.

Sample Properties

The properties of the plant samples received at Amax R&D are summarized below:

	Ayrshire		Lady Dunn		Wabash
	Fine Refuse	Centrifuge	Vorsiv U'flow	28x100m	-65m Fines
As Rec'd Solids, %	15.10	86.29	19.66	98.94	
Ash, % dry	64.47	26.79	34.39	30.56	23.90
Total Sulfur, % dry:	1.26	2.93	0.67	0.85	1.92
Particle Size, wt %:					
Passing 28 mesh	98.8	65.5	100.0	100.0	
Passing 48 mesh	96.3	26.8	>95.0		100.0
Passing 100 mesh	90.6	7.8	83.1	0.0	86.5
Passing 325 mesh	78.4	1.7	60.4	0.0	

Three-product washability tests were made on the Ayrshire and Lady Dunn samples. Significant amounts of good coal containing less than 11 percent ash were found in each sample. In addition, there was significant rejection of pyritic sulfur to the sink products, particularly in the case of the two Ayrshire samples.

Froth Flotation of Ayrshire Fines

Batch and continuous-flow laboratory flotation tests were performed on the Ayrshire coal fines to provide a quantitative basis for the engineering feasibility analysis advanced column flotation at that plant. An important objective of this testing was to determine the likely yield of clean coal and its quality and to obtain operating and plant design data to quantify parameters having an impact on process economics.

Denver Cell Batch Flotation

Denver cell tree-flotation tests were performed on the fine refuse and the centrifuge cake to provide release analysis curves. A second test was made on the centrifuge cake after it had been ground for 30 minutes to essentially passing 100 mesh. The knee of each of the curves was at 90 percent yield of the higher heating value in the respective samples. At that point, the clean coal from the fine refuse contained 10 percent ash and the clean coal from the centrifuge cake contained 12 percent ash. Grinding the centrifuge cake shifted the ash content of the resulting clean coal to the left to 8 percent ash. Flotation reduced the Ayrshire fine refuse to 10 percent ash and reduced the SO_2 emission of the coal down to 3 lb/MBtu. Cleaning also reduced the sulfur emission of the centrifuge cake, but only to about 4 lb of SO_2 per MBtu.

Initial assessments of flotation kinetics and retention times were provided by batch time-recovery tests on the three feed stocks. The coal in the centrifuge products was faster floating than the coal in the fine refuse, taking only 4 minutes to reach maximum yield compared to the 8 minutes for the coal in the refuse. The difference was probably due to the fine particle size of the coal and the large amount of clay in the refuse slurry. The sulfur was slower to float than the coal in the samples.

A rougher-cleaner batch flotation test confirmed the grades, recoveries and flotation times indicated by the release analysis and time-recovery tests. Glycol based M-150 was found to be a more potent frother than MIBC during subsequent reagent comparisons. It was more persistent during the cleaner flotations and appeared to produce finer bubbles. Unfortunately, the extra coal recovered with the M-150 frother was accompanied by significantly more ash and sulfur than the coal recovered with MIBC.

Continuous Column Flotation

CAER performed continuous laboratory flotation tests on the Ayrshire fine refuse using a 2-inch diameter generic Ken-Flote™ column with an internal aeration system. Parametric tests were conducted on the slurry to investigate the effects of varying aeration, wash water and feed rates on higher heating value (HHV) recovery and the ash content of the clean coal. The slurry was diluted to 10 percent solids for these tests, and 2 lb MIBC frother and 2.0 lb fuel oil were used per short ton of solids in the slurry.

Increasing the aeration increased the heating value recovery but had little impact upon the amount of ash remaining in the clean coal. The best recovery was at 6 standard liters/minute aeration where the HHV recovery was 99.7 percent and the product coal contained 9.96 percent ash. This recovery and product grade agreed well with the Denver cell release analysis curves.

The use of wash water had a significant impact upon the separation. The clean coal contained 17.0 percent ash when no wash water was used and always less than 12.3 percent ash when wash water was used. The best performance was with 0.4

liters/minute wash water where 95 percent HHV recovery was achieved with the resulting clean coal containing 9.5 percent ash.

As the feed rate increased, the heating value recovery declined and the amount of ash in the clean coal increased. The latter effect suggested that the 0.4 liter/minute of wash water added during each of the three tests was not enough to rinse the fine clay thoroughly from the froth when the column was pushed to capacity. A feed rate of 6 kg/hr of solids or 1 liter/minute of feed slurry, which translated into 6 minutes of retention time in the column, was best for this slurry.

The consensus of the laboratory flotation tests was that a 10 percent ash product can be prepared from the Ayrshire fine refuse slurry at 95 percent recovery of the heating value in the slurry (or about 80 percent MAF coal recovery). Operating conditions for such a separation in the 2-inch column were 1.0 liter/minute of 10 percent solids feed slurry, 0.4 liter/minute wash water and 4 standard liters/minute aeration.

Selective Agglomeration of Ayrshire Fines

Arcanum performed batch laboratory-scale selective agglomeration separations on the Ayrshire coal fines using kerosene and diesel fuel as bridging liquids. Asphalt was mixed with the bridging liquid at times to activate agglomeration and serve as a binder.

At least 9.3 percent bridging liquid, on a MAF coal basis, was required to form pellets from the fine refuse that were large enough to be retained on a 100-mesh sieve. However, the microagglomerates which formed when adding 4.5 percent bridging liquid could be recovered by froth flotation. Agglomeration of the fine refuse with kerosene alone resulted in poor phase separation and unsatisfactory yields of screenable material. The addition of 0.2 to 0.4 percent asphalt (based on product weight) to the kerosene improved the agglomeration and allowed recovery of 85 percent or more of the heating value in the Ayrshire fine refuse.

The clean agglomeration products prepared from the refuse stream contained between 4.24 and 7.53 percent ash, which was lower than the ash content of the comparable column flotation products.

The agglomerated product recovered from the centrifuge cake by froth flotation contained 10.23 percent ash. The agglomerated centrifuge products recovered by screening contained considerably more ash because coarse mineral matter was retained on the test sieve along with the pellets of clean coal.

It did not appear from these results that further selective agglomeration testing was warranted on the Ayrshire products. Because of the cost of the diesel fuel and kerosene bridging liquids, the only combinations which seemed to be at all practical were those where less than 5.0 percent bridging liquid were combined with froth flotation for collecting the agglomerated coal.

Froth Flotation of Lady Dunn Fines

Batch and continuous-flow laboratory flotation tests also were performed on Lady Dunn coal fines to provide a quantitative basis for feasibility studies on near-term applications at that plant. As with the Ayrshire application, it was important during this testing to project the likely yield of clean coal and its quality and to obtain operating and plant design data for parameters having an impact on process economics.

Denver Cell Batch Flotation

Denver cell tree-flotation tests were made on both the Vorsiv underflow feeding the mechanical cells in existing plant and the 28x100-mesh coal expected to be included with the flotation feed in the expanded plant. A second test was made on the 28x100-mesh cake after it had been ground for 20 minutes to essentially passing 100 mesh since the washability testing indicated significant ash mineral and pyrite locking with the coal in the 1.6 specific gravity float fraction.

The knee of each of the release analysis curves plotted from the tree-flotation tests was around the 90 percent heating value recovery point At that point, the clean coal from the Vorsiv underflow contained 8 percent ash while the clean coal from the unground 28x100-mesh coal contained 13 percent ash. Grinding the 28x100-mesh coal shifted the ash content of the resulting clean coal to the left to about 8 percent ash. Flotation also reduced the sulfur content of the coal by a small amount.

An initial assessment of flotation kinetics and retention times were provided by batch time-recovery tests on the three samples. The 28x100-mesh coal was faster floating than the coal in the Vorsiv underflow, but flotation was essentially complete after 4 minutes in each case. The Lady Dunn coal did not contain much pyrite so sulfur distributions followed the coal distributions.

A rougher-cleaner batch test was next performed on the fine refuse. The flotation time was set at 3 minutes which should produce a 90-percent heating value yield according to time-recovery tests and 8 percent ash in the clean coal according to the release analysis plot. Actual results were 82 percent heating value yield at 6.8 percent ash. As noted with the Ayrshire fine refuse, M-150 was a more potent frother than the MIBC but tended to pull more ash into the froth along with the clean coal.

Continuous Column Flotation

CAER also performed continuous laboratory column flotation tests on the Lady Dunn Vorsiv undersize using the 2-inch diameter generic Ken-Flote™ column. Parametric tests were conducted on the slurry to investigate the effects of varying aeration, wash water and feed rates on HHV recovery and the ash content of the clean coal. The slurry was diluted to 8.9 percent solids for these tests, and 0.5 lb MIBC frother and 0.5 lb fuel oil were used per short ton of solids in the slurry.

Varying the aeration rate had little impact upon the recovery of the heating value from the Vorsiv underflow. On the other hand, it did have a significant impact on the amount of ash reporting with the froth. Increasing the aeration rate from 2.0 standard liters/minute up to 5.0 standard liters/minute almost doubled the amount of ash in the clean coal -- from 5.4 percent up to 10.4 percent. The results of the two tests at 2.0 and 4.0 standard liters/minute were better than one would expect from the release analyses curves.

The use of wash water had a significant impact upon the separation. Clean coal recovery declined sharply when 0.6 and 0.8 liters/minute wash water were used, perhaps because of the effect of the extra dilution on the retention time of the slurry in the column. The extra wash water did improve the grade of the clean coal but that would be expected considering the lower recovery. The best performance was with 0.4 liter/minute wash water where 95 percent HHV recovery was achieved with a product containing 9.6 percent ash.

As the feed rate to the 2-inch column increased, the heating value recovery declined showing that the carrying capacity of the column was being pushed. A feed rate of 5.3 kg/hr of solids or 1 liter/minute of feed slurry, which translated into 6 minutes of retention time in the column, was best for this slurry.

The consensus of the laboratory flotation tests was that a 6 to 8 percent ash product can be prepared from the Lady Dunn Vorsiv underflow at 95 percent recovery of the heating value in the slurry (or about 90 percent MAF coal recovery). Operating conditions for such a separation in the 2-inch column were 1.0 liter/minute of 8.9 percent solids feed slurry, 0.6 liter/minute wash water and 4 standard liters/minute aeration.

About two years later, after the project team had evaluated the initial laboratory studies described above and found the proposed application to have merit, further laboratory testing was done on a fresh sample of Lady Dunn cyclone overflow flotation feed slurry that was similar to the Vorsiv underflow described above. These tests were conducted at CCMP in a 2-inch Microcel™ column, the type of column proposed for installation during the plant expansion. A grade-recovery plot of the Microcel™ results showed 90 percent heating value recovery of coal containing slightly under 10 percent ash and generally agreed with the CAER observations. It was also learned from these tests that a 21-foot column height would be sufficient for this application and that the solids concentration in the feed slurry (6.5 percent) was high enough that the column would not be hydraulically overloaded. In other words, the capacity of a column cleaning this slurry would be limited only by its froth carrying capacity (cross-sectional area) and not by retention time considerations.

Selective Agglomeration of Lady Dunn Vorsiv Underflow

Arcanum performed batch laboratory-scale selective agglomeration separations on the Lady Dunn Vorsiv underflow using kerosene and diesel fuel as bridging liquids. The Lady Dunn coal responded to selective agglomeration better than did the Ayrshire coal, so it was not necessary to add asphalt during these tests.

It was found that more diesel fuel bridging liquid would be needed than kerosene if the agglomerates were to be recovered by a screen separation. However, equally good recovery of clean coal was obtained with 2.0 percent diesel fuel and 2.0 percent kerosene when the agglomerated coal was recovered by froth flotation. Over 97 percent of the heating value was recovered from the 2.0 percent bridging liquid froth recovery tests, and the clean coals contained between 7.30 and 8.00 percent ash.

Froth Flotation of Wabash Fines

The decision to include advanced flotation of the natural fines in Illinois No. 5 coal as a near-term application was based upon laboratory and bench-scale testing that had been done a year earlier to support a Clean Coal Technology V submission. One part of that proposal was to install column flotation in the Wabash Preparation Plant in order to recover clean coal from the natural fines that were being rejected by desliming cyclones. The amenability of these fines to froth flotation had been demonstrated at CCMP using 2-inch and 8-inch Microcel™ columns. The fine coal responded very well to the column flotation. Over 90 percent combustible recovery was achieved during one test where the resulting clean coal contained only 5.0 percent ash. A 55 percent rejection of pyrite, a particularly important consideration at Wabash, was especially noteworthy.

ECONOMIC AND TECHNICAL FEASIBILITY OF PROPOSED APPLICATIONS

Bechtel performed an engineering analysis of the economic and technical feasibility of the proposed near-term applications, that is, column flotation and selective agglomeration at Ayrshire and Lady Dunn and column flotation at Wabash. They considered three marketing options for the clean coal to be produced by each application, namely 1) produce dewatered centrifuge cake for blending with the existing production, 2) produce dry powder fuel from the centrifuge cake, and 3) produce briquettes from the dry powder fuel.

Capital and Processing Costs

During their analysis, Bechtel found that between 21 and 98.8 st/hr of good quality clean coal would be produced by the proposed applications. This was new production in the Ayrshire and Wabash cases. As part of the economic analysis, Bechtel estimated the cost of installing the advanced circuits in the three plant locations and projected the total processing costs for operating the circuits, including capital charges. The projected capital costs, in 1993 dollars, for installing the circuits in each plant were as follows:

	Ayrshire Plant		Lady Dunn Plant		Wabash
	Flotation	Agglomeration	Flotation	Agglomeration	Flotation
Advanced Cleaning	$3.66M	$6.80M	$1.50M	$1.60M	$9.16M
Thermal Drying	5.36M	4.22M	3.4M	1.7M	5.4M

Specific installation costs for briquetting circuits were not determined for the three plants since there was no test data available for specifying equipment selection parameters. An allowance for capital charges was included in the subsequent briquetting processing cost, though. Figure 1 compares the combined capital charges and operating and maintenance costs for producing clean coal at each location for each of the three marketing options.

Producing centrifuge cake for blending with current plant production was the lowest-cost option at each location. The cost of producing centrifuge cake after column flotation cleaning ranged from $5.63/st at Lady Dunn up to $8.73/st at Wabash. Column flotation was also less expensive than selective agglomeration at Ayrshire and Lady Dunn, although the difference was only $3.18/st at Lady Dunn. Most of the difference in cost between column flotation and selective agglomeration was due to O&M charges, especially for electric power and the fuel oil used as the bridging liquid. There was a larger difference between the two cleaning costs at Ayrshire because it was more difficult to agglomerate Ayrshire coal than it was to agglomerate Lady Dunn coal.

Drying added between $7.36/st and $10.65/st to the total processing cost at the three locations. The high and low ends of the range were for drying agglomeration clean coal and flotation clean coal, respectively, at the Ayrshire location. Because of the oil used for bridging the coal particles, the centrifuged agglomeration coals were expected to contain less residual moisture to be evaporated than the centrifuged flotation clean coals, an advantage for agglomeration. However, in this comparison the moisture reduction advantage failed to overcome the cost of the additional bridging liquid required to agglomerate Ayrshire coal.

From published reports and past Bechtel experience, it was estimated that briquetting would add between $6.17/st and $7.26/st to the processing cost. This led to total processing costs between $24.02/st and $36.06/st for briquetted clean coal on a bone-dry basis. On a heating value basis, the total processing cost, including briquetting, ranged from $0.84/MBtu for flotation clean coal at Lady Dunn on up to $1.32/MBtu for agglomeration clean coal at Ayrshire.

Discussion of Economic Comparisons

The projected processing costs at the three locations, Ayrshire, Lady Dunn and Wabash, were not really comparable since they reflected differences in site conditions, utility rates and feed material characteristics which were very site specific. For example, the solids content of the feed slurry had a significant effect on the flotation cell volume and was a major factor affecting the capital and operating costs of the flotation circuits. To maintain an acceptable retention time in the columns, the required volume of the columns increased as the solids content of the feed slurry decreased. Feed slurry solids content at Ayrshire, Wabash, and Lady Dunn were 11.0, 4.2, and 2.8 percent, respectively.

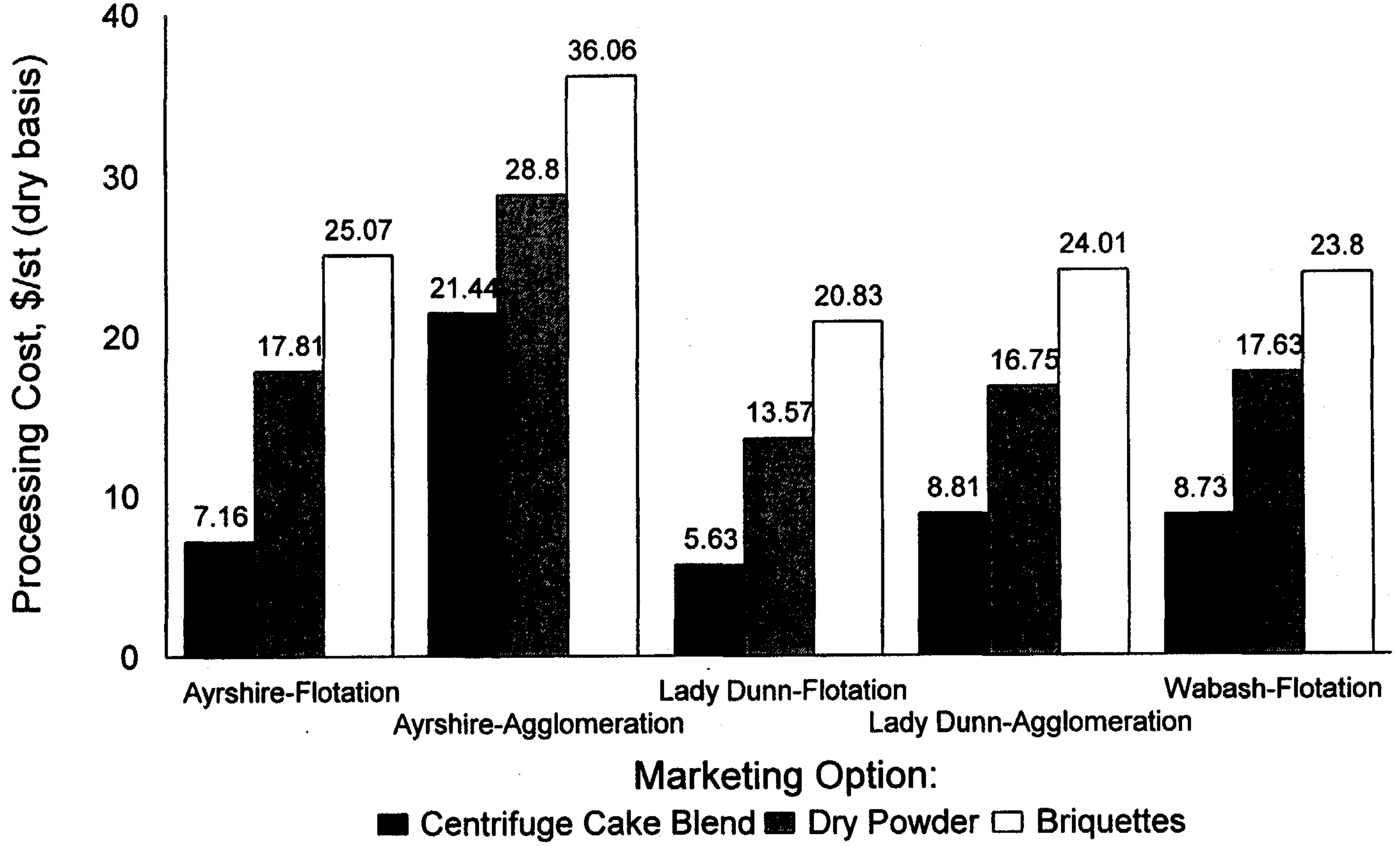


Figure 1. Processing Cost Summary for Plant Location and Marketing Options
(1993 Prices, Total Processing Cost includes Capital and O&M Charges but not the Cost of the Coal)

Flotation and agglomeration characteristics of the coal were other factors which affected processing costs. The Ayrshire fine refuse coal had poorer flotation and agglomeration properties than the Lady Dunn coal. This difference meant that extra flotation and shearing/mixing times were needed. Also, twice as much bridging liquid was required for agglomerating the coal in the Ayrshire fine refuse as needed for the Lady Dunn fines. These were some of the reasons that the Ayrshire applications were somewhat less attractive cost-wise than the Lady Dunn and Wabash applications.

Screen-bowl centrifuges for dewatering the fine coal accounted for a major part of the capital charges. The Lady Dunn Plant had spare centrifuge capacity, and also thickener capacity, for use in the column flotation and selective agglomeration circuits. This was part of the reason that the Lady Dunn applications tended to be more attractive than similar applications at the other two plants. On the other hand, the Wabash column flotation application benefited from the larger scale of the operation, particularly with respect to the drying and briquetting circuits.

These processing cost projections can be refined by further testing and process development, particularly in the drying and briquetting areas where little or no test data were available.

Technical Assessment of Applications

The technical risks and benefits of the processing options were studied during the engineering analysis. The three distinct processing options which were considered were 1) the fine coal cleaning procedure, 2) production of thermal dried fuel, and 3) production of briquettes.

Technical Risks in Column Flotation and Selective Agglomeration

For coal cleaning plants, major issues to be considered during a technical risk analysis are a) the characteristics of the feed coals and b) the efficiency of the process producing the expected quality and quantity of the product. Further, the combined characteristics of the feed coal and the process affect the plant design parameters used to develop capital and O&M (operating and maintenance) cost estimates. These design parameters influence the number and type of equipment items required and their cost, as well as O&M costs such as reagent consumption and power requirements.

Coal Characteristics: The characteristics of the feed coal play a vital part in determining the quality and the quantity of clean coal produced in a preparation plant. The column flotation and selective agglomeration circuits included in this study used streams from existing coal cleaning plants as feed stock. Unlike new plants designed to process coal from seams that have not yet been fully developed, the circuits proposed for this study will not face risks associated with unfamiliar feed material. Future supplies of feed coal will be derived from areas close to the areas currently being mined, so variations in coal quality can be projected with some certainty for future years. With this assurance, on-site scale-up tests of the technologies should provide confidence in their future performance.

Dewatering operations for clean coal and tailing/refuse are a major component of capital and operating costs for coal preparation plants. A higher than expected moisture level in the dewatered coal will severely limit the amount of the fine coal that can be blended with current production of clean coal without exceeding contract stipulations for the heating value and moisture content of the combined shipments. Also, a higher moisture content will increase operating costs if the product has to be thermally dried.

The Ayrshire and the Lady Dunn Plants pumped their fine refuse into disposal ponds as slurry without dewatering. However, dewatering or filtering characteristics of the refuse from fine coal cleaning systems are a vital concern for preparation plants which dewater/filter the fine refuse for disposal as at the Wabash Plant. Fortunately, the existing thickener and filter at the Wabash Plant were expected to be adequate for the *reject slurry* from column flotation.

Testing flow properties of the dewatered coal should be a part of the product characterization tests, as flow properties have a significant impact on the design of handling and drying systems. Moisture content and particle size are some of the most important factors affecting coal flow properties. In particular, the flow properties of clean coal agglomerates has to be evaluated as industrial experience with this material is limited.

Process Characteristics: Even though column flotation technology has been applied commercially in the mineral processing industry for many years, its application in coal cleaning has just begun. The development effort presents a challenge as it involves design of industrial column flotation units and integrated flotation systems to yield clean coal with targeted high quality and nearly complete heating value recovery. Scale-up to the required commercial sizes has to be approached with caution, as penalties for shortcomings, either in clean coal quality of quantity, could be severe.

The record of selective agglomeration and similar oil-based agglomeration processes has been spotty. In addition to the high cost of the fuel oil, the marketability of clean coal laced with fuel oil has been an impediment for wide acceptance of the process. Among other things, fuel oil in coal tends to adversely affect the life of ordinary rubber belt conveyors used in coal handling systems. Objectionable smell from oil has also been a problem for such coals. These issues have to be addressed and resolved before plants can be designed and built.

Technical Risks in Thermal Drying

Several processes for thermal drying fine material are available that are based on proven technology. However, fire and explosion hazards presented by fine coal drying systems, combined with requirements to meet environmental regulations governing gaseous emissions, make construction and operation of drying plants complicated and expensive.

Technical Risks in Briquetting

For each powder material to be compacted or briquetted, the most appropriate process conditions (which include operating temperature and pressure, type and quantity of binder, and post-briquetting treatment needs such as curing) are best determined by testing. Test data in this regard for the fine coal products from the Ayrshire, Lady Dunn and Wabash Plants were not available at the time so the Bechtel study discussed a generic briquetting system to convert dried clean coal from the column flotation and selective agglomeration circuits into lumps. In view of the enhanced marketability of the product after reconstitution, compacting or briquetting testing should be included in the product characterization test program.

Benefits of the Near-Term Applications

Recovery of high-quality clean coal from preparation plant streams that are now pumped or hauled to waste disposal sites will benefit the coal industry. Such streams pose a disposal problem to plant operators because the fine coal in them cannot be separated efficiently from the ash and sulfur minerals by conventional technology. Near-term application of advanced column flotation and selective agglomeration technologies to process these streams will allow preparation plant operators to recover and sell this coal without incurring additional expenses for mining or crushing. Such applications will also reduce waste disposal costs. Due to the fine particle size of the solids in the streams being processed, the ash minerals should be well liberated and the quality of the resulting coal will be better than the quality of existing production from a preparation plant. The benefits, in summary, are a) a significant increase in the quantity and quality of clean coal produced and in revenue for the preparation plant at a nominal increase in costs, b) reduced waste, c) improved environment due to the reduced use of waste disposal facilities, and d) better utilization of coal resources in this country.

Viability of Near-Term Applications

The economic and technical viability of near-term applications of these advanced technologies depends to a large extent on the specific site and the relationship of that site to the marketplace. As indicated above, the estimated processing costs for the clean coal on a dry coal basis range from a low of \$5.63/st to a high of \$36.06/st depending on the cleaning technology used, the additional drying and briquetting operations performed on the clean coal, and the specific preparation plant site. Costs for the column flotation options were significantly lower than for the selective agglomeration options. In the East and Midwest, coal similar in quality to the column flotation product sold for \$25 to \$35/st in 1993. Cyprus Amax Coal Company was aware of specific instances where mine operators paid in excess of \$35/st for high-quality coal for use in blending. The study indicated that there was a large margin between the estimated cost of recovering fine coal and its market price, even if the coal had to be dried and briquetted. The available margin amply justified further development of the technologies for near-term applications, particularly for column flotation, followed by drying and reconstitution of the fine coal into lumps.

Recommendation of Team

In view of the encouraging economic and technical assessment of the column flotation near-term applications, the project team, and with the strong support received from Cyprus Amax Coal Company, agreed to recommend larger-scale column flotation testing at the Lady Dunn Preparation Plant.

COLUMN FLOTATION TESTING AT LADY DUNN PREPARATION PLANT

In response to the favorable assessment of column flotation by the project team, pilot testing of a 30-inch diameter Microcel™ column began at the Lady Dunn preparation plant in June, 1995 in order to confirm the laboratory results and to obtain additional scale-up information. The recovery of the coarser particle sizes of coal was of particular interest during this work.

The Lady Dunn flotation feed typically contained around 40 percent ash and had a high percentage of minus 325 mesh coal and clay in the slurry. Column performance was evaluated from the percentage recovery of the coal in various particle-size fractions and from the ash content of the products. Operating parameters such as feed rate, aeration rate, frother and collector dosage were varied to determine their effects on the recovery of the various particle sizes of coal. The plant had existing mechanical flotation cells so the test results could be directly compared to conventional technology.

A 30-inch diameter column was chosen for the study because that column diameter would provide a reasonable froth travel distance to allow time for coarser particles to drop out of the froth zone back down into the slurry as one would expect in a full-size column.

The Lady Dunn Plant

At the time of the pilot testing, the Lady Dunn Plant was mid-way through an expansion program. The flowsheet consisted of heavy-media vessels for coarse coal (+1/4 inch), heavy-media cyclones and Deister tables for 1/4-inch x 100-mesh coal, and conventional flotation on the minus 100-mesh overflow from desliming cyclones. A number of streams were examined for the column testing. Finally, a stream of minus 1-mm raw coal screen undersize stream was selected for the bulk of the parametric testing.

30-inch Column Circuit Description and Operation

The 30-inch Microcel™ test column has a capacity of 0.5 to 1 tph of clean coal for most applications. Microbubbles were created by injecting air into tailings slurry pumped through in-line mixers back into the bottom of the column. Wash water was added at the top of the column and also as push water to the froth in the overflow launder. The system was fitted with instrumentation for measuring and controlling wash water, air and slurry flows and the pulp level in the column. The instrumentation also provided an indication of the air fraction in the column. A sight glass provided a view of the pulp/froth interface area for assessment of turbulence, approximate bubble size, and excess air flow.

Testing Results and Discussion

Information was gathered from preliminary testing and from two series of parametric tests. The feed for the preliminary testing was from the classifying cyclone overflow stream. Results were excellent and compared well with the earlier laboratory results.

Parametric Testing

There were two series of parametric tests. These tests were to determine the effect of various operating variables on the performance of the flotation column, specifically the recovery of the coarser size fractions of the coal. Some irregularities in the results were seen because it was difficult to provide a consistent feed to the test column due to unplanned variations in the operation of the main plant.

Parametric Tests - First Series

The intent of the initial series was to vary key operating variables from low to high in order to determine likely operating points for the second series. In effect though, the first set of results provided a more consistent data set than the second. Even though the first series was not designed as a parametric set, when the main parameters (i.e. frother dosage, collector dosage, and feed rate solids) were entered into a statistical analysis program, good correlations were found and definite trends were seen.

Nearly all of the results from the first series fell along a single grade-recovery curve for each particle size range. Results move along an existing grade-recovery curve due to variations in the loading of the bubbles (i.e., space available for attachment). Changes in the specific characteristics of the coal particles (i.e., degree of liberation and hydrophobicity) result in new grade-recovery curves. The close fit to a common grade-recovery curve indicated that entrainment of non-floatable material in the froth was not a problem during this series of tests. In other words, the wash water flow was sufficient to remove entrained high-ash particles from the froth zone.

The best recovery seen during each test was for the 0.150 x 0.045 mm (100 x 325 mesh) size fraction, and the 0.045 mm x 0 recovery was always slightly less. Most often combustible recovery dropped off at the coarser sizes. Three particle-size classes, 0.25 mm x 0, 0.5 x 0.25 mm, and 0.5 mm x 0, were considered separately for the statistical analysis. A quadratic model fit best. The parameters which had the most significant effect on combustible recovery were feed rate, frother dosage, and diesel fuel dosage. The parametric model fits had R-squares of at least 0.94 for the three particle-size classes.

Three dimensional plots were prepared of the combustible recoveries predicted by the statistical models. They showed that at a low frother dosage, increased feed rate reduced combustible recovery from the 0.25 mm x 0 fraction. This was as expected since the bigger bubbles which formed under those conditions were quickly overloaded since their limited surface area restricted their carrying capacity for coal particles. The same performance was predicted by the models for the medium frother dosage except that at the higher feed rate, recovery would improve over that with the lower frother dosage. At a high frother dosage little change in recovery was noticed with changes in feed rate, indicating sufficient bubble surface area for carrying the full range of particle sizes available in the feed slurry.

Variation in the diesel fuel dosage had little effect on the flotation of 0.25 mm x 0 coal except that some improvement in recovery was predicted at higher frother dosages. This probably was because together the smaller bubble size and the increased collector dosage improved the flotation rate constant and provided the extra carrying capacity needed to collect middlings particles that were previously being rejected.

There were differences in the plots for the coarser 0.50 x 0.25 mm particle size range coal. At the lower frother dose, combustible recovery was highest at the low feed rate just as for flotation of the smaller particles. Unlike the finer sizes, however, diesel fuel dosages had a major effect upon recovery of the coarse coal. At low frother and low feed rates, the recovery actually dropped with increased collector addition. This was probably because the excess diesel fuel, above that needed to coat the coal, depressed froth formation and resulted in the formation of larger bubbles with less surface area. In such cases, the fine coal particles preferentially adhere to the bubbles and block access by the coarser particles.

At the medium frother dosage and a low diesel fuel dosage, the relationship between feed rate and recovery was similar to that of the low frother dosage; that is, increased feed rate meant lower recovery. At the low feed rate, increasing the diesel fuel dosage appeared to lower recovery due to the decreased effectiveness of the frother. At the highest diesel dosage the recovery increased again due to the increased particle hydrophobicity brought about by the large amount of collector available in the slurry.

At a high frother dosage, combustible recovery appeared to have been affected only by the diesel fuel dosage. At the low diesel fuel dosage the recovery of coarse coal was depressed, probably due to the "wetting" of its surface by the excess frother. At higher diesel fuel dosages the coal surfaces were not "wetted" by the frother and maximum recovery was projected by the model.

Overall, it was shown that 0.50 x 0.25 mm coal can be recovered at specific conditions nearly as well as the finer coal. The actual size-by-size results also show why flotation is seldom utilized to recover coal above 0.5 mm in particle size. Even with the best combination of parameters, the combustible recovery began to drop off rapidly as the size of the particles increased above 0.50 mm.

Parametric Tests - Second Series

The intent of the second series of parametric testing was to further determine the effect of bubble size and air fraction on coarse coal recovery. To do this, air volume and frother dosage were varied. Feed rate was a third variable.

Although the earlier testing had shown that the diesel fuel dosage also affected the coarse coal recovery, the intent was to remove it as a variable by holding the diesel dosage relatively constant. Due to variations in plant operation, screen wear in the feed preparation system, and raw coal pumping surges (all unique to this test series) the actual percent solids in the column feed varied considerably. The variation, from 7 to 14 percent solids, had an unintended impact on the actual diesel fuel dosage as well. Although the volumetric dosage of diesel fuel was held constant for a given feed flow, the grams per tonne of feed dosage varied with the percent solids changes. Since the diesel fuel tended to coat the fine coal particles first, with only the remaining oil being available to coat coarser particles, any variation in the fraction of finer coal in the feed caused the amount of diesel fuel available for coating the coarse particles to vary considerably.

The same three particle size classes were considered for the second parametric test series as considered for the first series, and the test results were entered into the Design Expert statistical computer program. Variations in feed, air and frother within the test ranges were found to have very little affect on percentage recovery of the 0.25 mm x 0 fine coal. For all three frother dosages, the lowest recovery was at the maximum feed and air flows. At these conditions the column would be at its most turbulent state which may explain the lower recovery under those conditions.

When reviewing the predictive plots for the coarser, 0.50 x 0.25 mm coal, though, the results were more erratic than for the finer fraction. At the low frother dosage the model predicted a higher recovery at the higher feed rate. This was contrary to normal flotation results since higher feed rates tend to overload the froth, causing lost recovery. The medium frother dosage showed a similar result although not as pronounced. It was obvious that something else was happening that would account for the deviations from predictions based on prior experience. At a low feed rate and high air flow, there was a high recovery of coal as one would typically expect. At the high frother dosage, the response plot also looked typical with a much higher recovery of the 0.50 x 0.25 mm coal at the low feed-rate, high air corner. This was expected. Given sufficient bubble surface area, coarse particles attach readily to bubbles. At the same time, though, many hydrodynamic situations arise in the column which can subsequently detach these particles from the same bubbles. On the other hand, fine coal particles are difficult to detach from bubbles once they have become attached to the bubbles.

Second Series Revisited

After extensive review and cross plotting of the variables and other operating parameters, the question of the inconsistent results from the second series was resolved. The major problem stemmed from the variation in the percent solids of the feed slurry. Above a threshold dosage of diesel fuel (around 1200 g/T for this system), the air fraction dropped rapidly. The decrease in the air fraction from the 10 to 13 percent range down to below 4 percent indicated formation of much larger air bubbles with less surface area for attachment of particles. Since the fine coal particles were more strongly attached to the bubble surfaces than were the coarse particles, the coarser particles were the first to be lost at high bubble loadings. The larger bubbles may also have caused increased turbulence that would result in detachment of coarse particles.

The statistical analysis was re-evaluated using diesel fuel dosage, frother dosage, and feed rate as variables. Air flow had been found to have a very small effect during the previous evaluation of these data. Changes in 0.25 mm x 0 coal recovery due to differences in frother dosage were again found to be small. The best performance was at the medium frother dosage while the lowest recovery was found at the extremes of high diesel fuel dosage, high feed rate, and low frother dosage. At the low feed rate, the diesel fuel dosage accounted for a slight increase in recovery at all but the lowest frother dosage.

Combustible recovery from the 0.50 x 0.25 mm fraction had a much broader range of response in the revised prediction model. A change in recovery at low diesel fuel dosages was the most significant variation observed. Recovery dropped considerably at all feed rates with the increasing frother dosage. At the higher frother dosages, increasing the diesel fuel dosage improved the recovery of the coarse coal by overcoming the effects of the excess frother. An unexpected response was the increase in recovery with increasing feed rate and low diesel dosage.

Conclusions of Pilot Testing

The test work in the 30-inch column illustrated very well the potential for coarse coal flotation in a properly operated system. Particles up to 0.25 mm in size floated consistently well. Coarse coal up to 0.50 mm in size also floated well, but coal recovery dropped off rapidly above that size. Since it is difficult to avoid misplaced material when separating fine particle sizes, making a nominal 0.25-mm cut and sending the minus 0.25-mm fraction to a flotation column should work well in most coal processing plants. As long as the misplaced coarse material in the feed slurry is smaller than 0.50 mm, the column can provide very good recovery of coal with a low ash content.

In traditional coal processing plant applications, the particle-size cut ahead of flotation is made at a nominal 0.150 mm (100 mesh). The difficulty in making such a fine cut results in a considerable amount of fine material (usually high in ash) in the coarser fraction. In all gravity separation devices designed for cleaning plus 0.150-mm material, much of the minus 0.150-mm material reports to the clean coal launder without cleaning (i.e., as high-ash raw coal). The difficulty in removing fines from clean coal streams results in higher ash final products. By utilizing wash water, a flotation column can remove the high ash slimes that would otherwise be entrained in the froth. Thus, it can handle slimes better than any other cleaning device readily available to a preparation plant operator, yet it can still clean the 0.25-mm particles which do not respond well to conventional flotation.

Indications are that column flotation will perform well at the Lady Dunn Plant. The original mechanical flotation cells produced an average of 14 to 16 percent ash clean coal at a 20 percent combustible recovery. Results from testing the 30-inch diameter column, on the other hand, indicate that clean coal containing 10 to 11 percent ash can be obtained from the 0.25-mm x 0 fines at a combustible recovery of 75 percent.

The success of this test work was made tangible by the installation of three Microcel^{TM} flotation columns, each four meters in diameter, in the Lady Dunn Preparation Plant. These are the largest known flotation columns for processing coal. Cyprus Amax Coal Company installed the columns in the plant on the basis of the good results achieved by the test work described in this report. The new columns have been successfully cleaning 0.25-mm x 0 coal and producing results that fit on the ash/recovery curves presented in this report.

AUXILIARY OPERATIONS

The pilot scale flotation investigation was supplemented with laboratory and bench-scale studies to dewater the clean coal froth from the 30-inch column and also to improve its marketability by conversion to CWF slurry fuel and by briquetting to a lump fuel.

Dewatering

Twelve drums of the clean coal froth were collected and shipped to the what is now the Federal Energy Technology Center at Pittsburgh for centrifuge dewatering tests using their GranuFlow process. The GranuFlow process involved mixing an asphalt emulsion called Orimulsion with the coal slurry before dewatering in order to reduce the amount of moisture remaining in the cake and to improve the handling properties of the fine coal. Performance of screen-bowl and solid-bowl centrifuges were compared, and cakes with the following percentage moisture contents were obtained:

	No Additive	6 - 8 % Orimulsion
Screen Bowl	39.4	35.2-35.7
Solid Bowl	34.8	31.0

The Orimulsion additions were also found to reduce the potential dustiness of the fine coal as measured by the amount of minus 100-μm material released when sieving dried centrifuge cakes. The Orimulsion additions improved solids recovery in the screen-bowl centrifuge as well.

In addition to the centrifuge testing, 122 laboratory vacuum filtration leaf tests were conducted on the froth slurry from the 30-inch column by Westech Engineering Inc.

personnel. The objectives of the leaf testing were to project the capacity and performance of both top-feed horizontal belt filters and bottom-feed drum filters. The laboratory evaluation included testing the benefits of layering spiral concentrate (available from a separate project at Lady Dunn) onto a horizontal filter ahead of the froth slurry.

Because of the residual clay in the Lady Dunn clean coal slurries, preflocculation was required to achieve good filtration performance. Severe filter cloth blinding occurred after a few tests so it was necessary to include a cloth washing step in the filtration cycle.

There were some ambiguities among the capacity and cake moisture projections which may have been due to the differing amounts of flocculant required for each situation. However, it was clear that filtering coarse spiral concentrate along with the froth slurry, either by layering or by premixing, offered little advantage with respect to capacity or moisture removal. A horizontal belt filter cycle appeared to offer a somewhat higher capacity on a lb/hr/sq ft basis than a drum belt filter cycle, but the moisture contents of the resulting cakes were about the same, that is, in the 34 to 43 percent range. Because these cake moistures were similar to the centrifuge cake moistures, Lady Dunn management decided to continue with their original plan to use a screen-bowl centrifuge for dewatering the column flotation froth after the plant expansion.

Slurry Preparation

Marketing clean coal from near-term column flotation as slurry fuel rather than filter or centrifuge cake was considered. Slurry preparation tests were performed on froth slurry from the Microcel™ testing at the Lady Dunn plant. The tests were on the froth slurry alone and on froth slurry blended with coarser slurry prepared by stage grinding spiral concentrate to minus 48 mesh. It was found that at a projected viscosity of 500 cP, slurry loadings of 62, 63 and 68 percent coal could be achieved for blends containing 0, 10 and 40 percent, respectively, of the ground spiral concentrate. In each case, the slurry contained one percent A-23 dispersant on a dry coal basis.

These results indicate that if a niche market were found in the Charleston area, one might sell the fine coal from the Lady Dunn plant as a slurry fuel containing about 60 percent coal. However, it appears at this time that dewatering the fines in a centrifuge and blending the cake with the normal plant production is the better alternative in terms of cost and marketability.

Briquetting

A portion of the clean coal from the 30-inch column testing was submitted to TraDet Inc. for binderless briquetting tests. Good quality specimens of the briquette production were returned by TraDet, who reported that the briquetting was done at near-ambient temperature on the flotation product after it had been air-dried to between 1.0 and 2.4 percent moisture. The briquettes contained 11.8 percent ash and 34.2 percent volatile matter and had an estimated heating value of 12,900 Btu/lb.

A model B-100A Komarek laboratory roll-press machine was used. The rolls were preheated to equilibrium operating temperature by briquetting waste material before switching to the test coal. Parametric tests were made at three roll speeds and at five hydraulic roll pressures between 1,300 and 2,800 psig on batches of the coal that had been dried to four differing moisture levels. At the product temperatures of 128° to 178° F, these pressures deform coal particles and fuse them together.

The crush strengths of the briquettes were between 50 and 200 lbs, and these strengths correlated well with the amount of energy transferred to the briquettes (between 8 and 29 kWh/ton). TraDet considers any strength over 100 lbs to be acceptable for briquettes such as these. The best briquettes were made when the feed coal had been dried to 1.0 percent moisture. The briquetted products from all 58 tests had acceptable moisture reabsorption, weathering and degradation properties. Based upon these results, TraDet suggested follow-up optimization testing in a pilot-size machine to allow scale-up of the laboratory briquetting performance to commercial production units.

CONCLUSIONS AND RECOMMENDATIONS

The conceptual engineering analysis of laboratory column flotation and selective agglomeration test results and the confirmation bench-scale and pilot testing of column flotation have shown that advanced physical fine-coal cleaning processes can be advantageously integrated into existing coal preparation plants. The following observations were made regarding this work:

- Column flotation can recover a lower-ash clean coal than the usual mechanical-cell flotation and at a higher recovery of combustibles. The following example is for the Lady Dunn application:
    - Microcel™ column – 10 to 11 percent ash clean coal, 75 percent recovery
    - Mechanical cells – 14 to 16 percent ash clean coal, 20 percent recovery
- Column flotation can be effectively applied to streams containing coal as coarse as 0.5 mm and, less effectively, as coarse as 1.0 mm.
- High-pressure binderless bench-scale briquetting was effective for reconstituting the clean coal.
- Selective agglomeration performance projected from laboratory testing was similar to or somewhat better than the performance of column flotation.

- Projected near-term application costs for producing dewatered clean coal by column flotation of raw coal fines were in the $5.60 to $8.70 per dry short ton range.
- Projected near-term application costs for producing dewatered clean coal by selective agglomeration with a non-recoverable bridging liquid such as diesel fuel were significantly higher than the projected cost of recovering the clean coal by column flotation. Selective agglomeration was particularly less competitive when cleaning midwestern Ayrshire coal which did not agglomerate as easily as the eastern Lady Dunn coal.
- Thermal drying of the clean coal for blending with the existing plant production or for separate sale as powder fuel adds $7.60 to $10.60 per short ton to the production cost of the coal recovered by advanced cleaning.
- The total projected cost of producing briquetted fuel (but not including the cost of the raw coal fines) was less than $25.10 per short ton for four of the five near-term applications evaluated.

The following recommendations are offered to operators of coal preparation plants:

- Advanced physical fine coal cleaning options should be considered for installation in new plants and when refurbishing or expanding existing plants. It is likely that additional revenue can be generated over the revenues from the "no fine coal cleaning" or the "mechanical-cell flotation" options.
- In order to reduce costs, agglomeration with recoverable bridging liquids such as heptane and pentane, should be explored as alternatives to fuel oil and diesel fuel.
- Methods for improving the marketability of the recovered fine coal, such as GranuFlow processing, conversion to CWF, powder fuel, and especially binderless briquetting, should be developed further.

INTRODUCTION

The Pittsburgh Energy Technology Center (PETC), now the Federal Energy Technology Center (FETC), Pittsburgh of the U. S. Department of Energy (DOE) awarded cost-sharing contract No. DE-AC22-92PC92208 on September 30, 1992 to an Amax-led team for "Engineering Development of Advanced Physical Fine Coal Cleaning for Premium Fuel Applications." The coal cleaning methods targeted by the program are the advanced column froth flotation and selective agglomeration processes researched and developed under the DOE Acid Rain Control Initiative (ARCI).

The program stresses the engineering development of processes for preparation of ultra-clean coal. The ultra-clean coal would be burned as a cost-effective premium fuel to replace a portion of the oil now firing utility and industrial boilers, and it could also be burned in advanced combustors now undergoing development. The major objective of this program is to identify suitable feed coals and to develop the design base for coal cleaning plants which can process such coals while recovering at least 80 percent of the heating value of the raw coal as a clean product containing

- Less than 0.6 pound sulfur per million Btu (258 grams per gigajoule).
- Less than 2 pounds ash per million Btu (860 grams per gigajoule) and preferably less than 1 pound ash per million Btu (430 grams per gigajoule).

Since it is expected that the ultra-clean coal will be burned in the form of coal-water slurry fuel (CWF), the design base will include provisions for conversion of the clean coal into CWF. The resulting CWF must be highly loaded, the project goal is 70 percent coal, to avoid derating the boilers. It is anticipated that a market for such fuel can open by the turn of the century, assuming the cost of producing ultra-clean coal in the form of CWF is less than \$2.50 per million Btu (\$2.37 per gigajoule) including the cost of the coal.

A secondary objective of the program is to develop the design base for near-term commercial applications of advanced fine coal cleaning technologies which would be suitable for integration into new or existing coal preparation plants for the purpose of economically and efficiently processing the coal fines wasted in many plants. The scope of the program includes development of the associated auxiliary systems required to yield a shippable, marketable product from the fines.

A further objective of the program is to determine the distribution of twelve toxic trace elements between product and refuse streams when cleaning selected coals by the advanced flotation and selective agglomeration processes.

A 2-t/h (1.8-tonne/hr) process development unit (PDU) has been designed and built to accomplish the project objectives. The advanced flotation technology has been tested in the PDU, and the selective agglomeration technology is now undergoing investigation in the unit.

This Topical Report discusses engineering studies conducted to determine the feasibility of utilizing the two advanced physical fine coal cleaning technologies in existing coal preparation plants in order to recover additional coal. The objectives of these studies, which were part of Task 3 Development of Near-Term Applications, are presented in this report along with summaries of the laboratory testing and conceptual design effort which preceded on-site pilot-scale testing at the Lady Dunn coal preparation plant in West Virginia. The report presents in some detail the results of pilot-scale testing of the selected process (column flotation) in the plant and also presents the dewatering, CWF preparation and briquetting testing conducted on the clean coal in order to prepare a marketable product from the fine coal. The conclusions drawn from the work are also presented along with a brief description of how advanced column flotation was included in the expansion of the Lady Dunn Preparation Plant.

PROJECT BACKGROUND

This section of the report provides general background on the project and its structure, schedule and organization. Specific details are provided for Task 3.

WORK BREAKDOWN STRUCTURE

The project is divided into four phases and eleven tasks, as outlined in the work breakdown structure presented in Table 1. As shown, there are parallel programs for developing the advanced flotation and the selective agglomeration processes.

The project focuses on the development of the two cleaning processes for preparing low-ash fuel from finely ground coal. However, Task 3 is an extension of project to specifically study the use of these same processes as a means for recovering fine coal lost in present-day coal preparation plants. Such applications represent immediate near-term benefits to be gained from this project and would complement the long-term gains achieved by producing premium fuel from coal.

Task 3 was divided into two subtasks as follows:

3.1 Engineering Analysis
3.2 Engineering Development
3.3 Dewatering Studies

Work on the three subtasks has been completed following a test plan submitted in 1993 [1]. The conceptual design aspects of Subtask 3.1 were reported to the DOE in a Topical Report titled "Task 3 Development of Near Term Applications, Subtask 3.1 Engineering Analysis Conceptual Designs and Cost Estimates" dated November 5, 1993 [2]. The remaining work on Subtask 3.1 and the engineering development work for Subtask 3.2 are presented in the Topical Report in hand. Virginia Tech is preparing a separate topical report for Subtask 3.3.

PROJECT SCHEDULE

Figure 2 shows the project schedule. The project started in October 1992 and is scheduled for completion in September 1997. Subtasks 3.1 and 3.2, which involved the study of the near-term applications began during November 1992 and testing was completed during September 1996.

PROJECT TEAM ORGANIZATION AND RESPONSIBILITIES

Figure 3 shows the project management organization chart and the primary responsibilities of the various team members. Amax R&D (and later its on-site subcontractor, Entech Global) along with team members, Amax Coal Company (later becoming Cyprus Amax Coal Company), Technology and Consulting at Bechtel Corporation and the Center for Coal and Mineral Processing (CCMP) at Virginia Polytechnic Institute and State University were responsible for conducting Subtask 3.1 and 3.2. Les Fish, who has been part of the Cyprus Amax Management Project Review

Committee was, in particular, responsible for planning and managing the test program at the test site. Project Team members, Arcanum Inc and the Center for Applied Energy Research (CAER) at the University of Kentucky, conducted laboratory tests for Subtask 3.1, and Westech Engineering Inc of Salt Lake City, Utah, and TraDet Inc of Triadelphia, West Virginia, were contracted to perform development work for the auxiliary dewatering and briquetting operations.

Table 1. Outline of Work Breakdown Structure

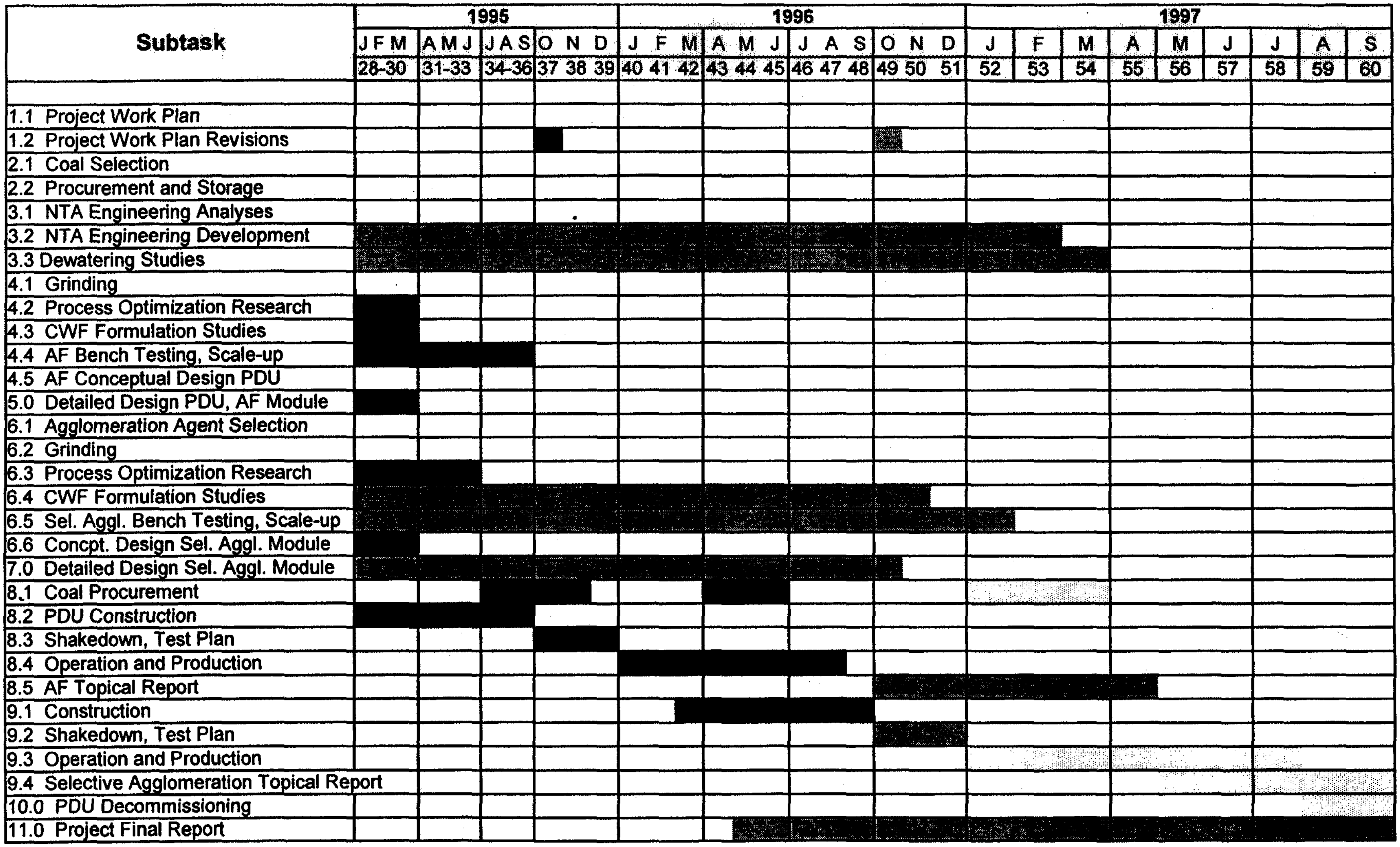
	Phase I. Engineering Analysis and Laboratory and Bench-Scale R&D
Task 1.	Project Planning
Subtask 1.1.	Project Work Plan
Subtask 1.2.	Project Work Plan Revisions
Task 2.	Coal Selection and Procurement
Subtask 2.1.	Coal Selection
Subtask 2.2.	Coal Procurement, Precleaning and Storage
Task 3.	Development of Near-Term Applications
Subtask 3.1.	Engineering Analyses
Subtask 3.2.	Engineering Development
Subtask 3.3	Dewatering Studies
Task 4.	Engineering Development of Advanced Froth Flotation for Premium Fuels
Subtask 4.1.	Grinding
Subtask 4.2.	Process Optimization Research
Subtask 4.3.	CWF Formulation Studies
Subtask 4.4.	Bench-Scale Testing and Process Scale-up
Subtask 4.5.	Conceptual Design of the PDU and Advanced Froth Flotation Module
Task 5.	Detailed Engineering Design of the PDU and Advanced Flotation Module
Task 6.	Selective Agglomeration Laboratory Research and Engineering Development for Premium Fuels
Subtask 6.1.	Agglomeration Agent Selection
Subtask 6.2.	Grinding
Subtask 6.3.	Process Optimization Research
Subtask 6.4.	CWF Formulation Studies
Subtask 6.5.	Bench-Scale Testing and Process Scale-up
Subtask 6.6.	Conceptual Design of the Selective Agglomeration Module
Task 7.	Detailed Engineering Design of the Selective Agglomeration Module
	Phase II. PDU and Advanced Column Flotation Module Testing and Evaluation
Task 8.	PDU and Advanced Column Froth Flotation Module
Subtask 8.1.	Coal Selection and Procurement
Subtask 8.2.	Construction
Subtask 8.3.	PDU and Advanced Coal Cleaning Module Shakedown and Test Plan
Subtask 8.4.	PDU Operation and Clean Coal Production
Subtask 8.5.	Froth Flotation Topical Report
	Phase III. Selective Agglomeration Module Testing and Evaluation
Task 9.	Selective Agglomeration Module
Subtask 9.1.	Construction
Subtask 9.2.	Selective Agglomeration Module Shakedown and Test Plan
Subtask 9.3.	Selective Agglomeration Module Operation and Clean Coal Production
Subtask 9.4.	Selective Agglomeration Topical Report
	Phase IV. PDU Final Disposition
Task 10.	Disposition of the PDU
Task 11.	Project Final Report

Revised, April 25, 1995

Subtask	1992			1993												1994											
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1.1 Project Work Plan	■	■	■																								
1.2 Project Work Plan Revisions												■												■			
2.1 Coal Selection			■	■	■	■	■																				
2.2 Procurement and Storage				■	■	■	■	■	■																		
3.1 NTA Engineering Analyses			■	■	■	■	■	■	■	■	■	■	■	■													
3.2 NTA Engineering Development					■	■	■	■	■	■	■	■	■	■	■												
3.3 Dewatering Studies																											
4.1 Grinding						■	■	■	■	■	■	■	■	■	■	■											
4.2 Process Optimization Research							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.3 CWF Formulation Studies											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.4 AF Bench Testing, Scale-up												■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.5 AF Conceptual Design PDU					■	■	■	■	■	■	■	■	■														
5.0 Detailed Design PDU, AF Module														■	■	■	■	■	■	■	■	■	■	■	■	■	■
6.1 Agglomeration Agent Selection					■	■	■	■	■																		
6.2 Grinding								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
6.3 Process Optimization Research											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
6.4 CWF Formulation Studies																										■	■
6.5 Sel. Aggl. Bench Testing, Scale-up																									■	■	■
6.6 Concpt. Design Sel. Aggl. Module																■	■	■	■	■	■	■	■	■	■	■	■
7.0 Detailed Design Sel. Aggl. Module																											
8.1 Coal Procurement																											
8.2 PDU Construction																											
8.3 Shakedown, Test Plan																											
8.4 Operation and Production																											
8.5 AF Topical Report																											
9.1 Construction																											
9.2 Shakedown, Test Plan																											
9.3 Operation and Production																											
9.4 Selective Agglomeration Topical Report																											
10.0 PDU Decommissioning																											
11.0 Project Final Report																											

Revised October 24, 1996

Figure 2. Project Schedule



Revised October 24, 1996

Figure 2 (Cont'd). Project Schedule

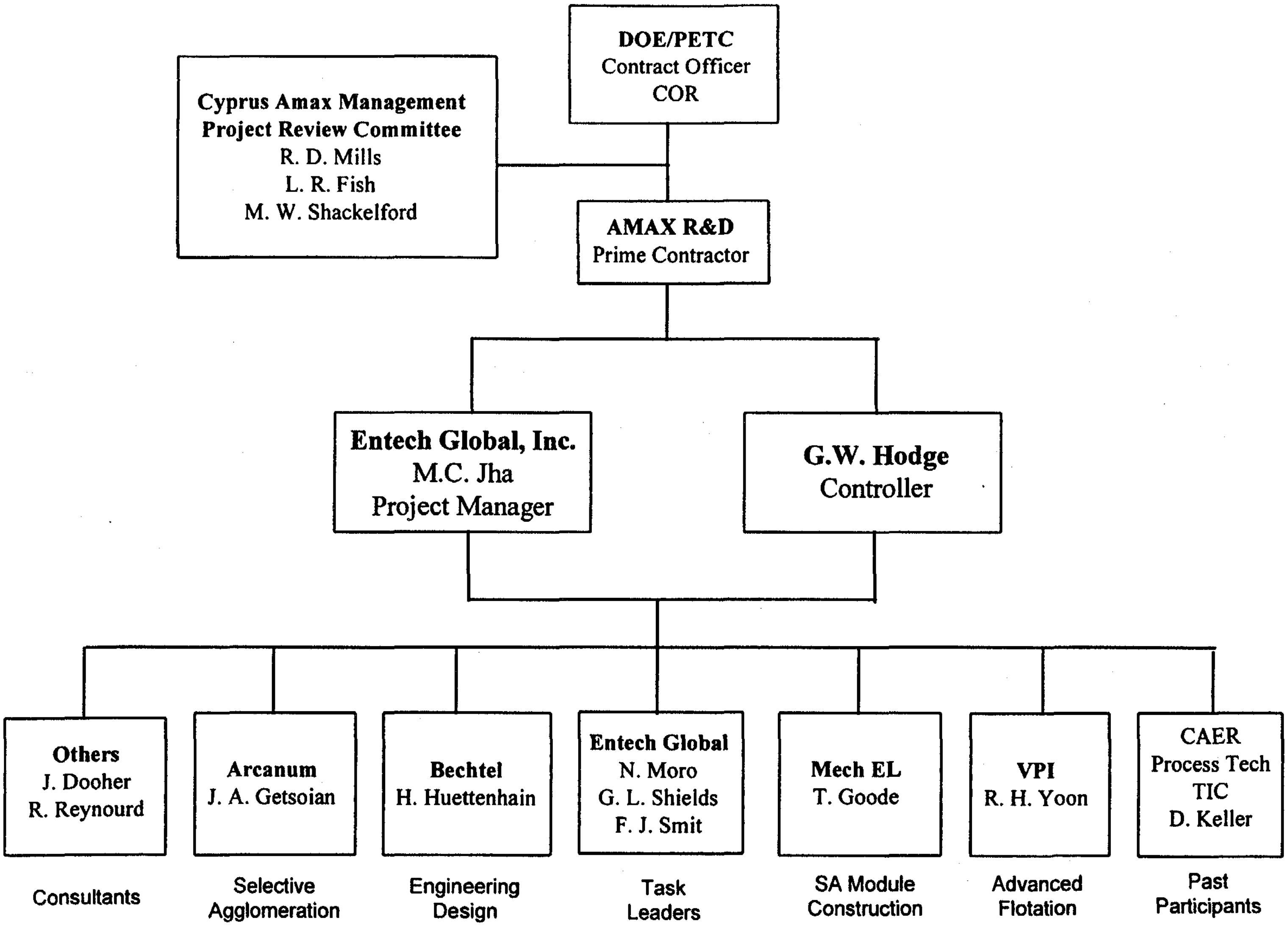


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Figure 3. Project Management Organization Chart

TASK 3 DEVELOPMENT OF NEAR-TERM APPLICATIONS

The task and subtask objectives, the approach and procedures followed to achieve the objectives, and the results of the subtask activities are discussed in the following sections of this report.

TASK OBJECTIVES

As indicated earlier, Task 3 is an extension of the premium fuel project to specifically address the use of advanced flotation and selective agglomeration processes for recovering fine coal lost in existing coal preparation plants. The goal of the task is to produce coal which can be sold in existing markets by one or both of the following strategies:

- Increase the percentage recovery of marketable coal from the ROM coal.
- Improve the quality and value of the marketable coal (heating value, sulfur or ash content, and handling characteristics) in a cost-effective manner.

If this goal can achieved, these applications would represent immediate near-term benefits that would be gained from the project and would complement the long-term benefits to be gained from the production of premium fuel from coal.

The task was originally divided into to two subtasks with related objectives. The first of these subtasks, Subtask 3.1 Engineering Analysis, had four objectives:

1. Identify potential applications of the two advanced fine coal cleaning processes in new or existing coal preparation plants.
2. Identify subsystems required to yield a near-term marketable product acceptable to customers.
3. Conduct preliminary assessments of cost, technical risk and economic viability of one or more near term applications of advanced flotation and/or selective agglomeration.
4. Select an application or applications for engineering development and testing to produce a marketable, shippable product.

The second subtask, Subtask 3.2 Engineering Development had, as it primary objective, the pilot-scale testing and engineering development of the selected application or applications. This objective included the engineering development of auxiliary subsystems required for plant integration and production of a marketable, shippable product.

Later, the contract was modified to include Subtask 3.3 Dewatering Studies to be performed by Virginia Tech. Results of this work will be presented in a separate report.

APPROACH AND SCOPE

A five-step approach was followed to accomplish the objectives of the task. The steps were as follows:

1. Survey, with close cooperation from division-level operating management, Amax Coal Company properties to determine which preparation plants were candidates for application of the new technologies. The factors to be considered included the extent of the fine coal losses in the various plants, the accessibility of the streams of fine waste coal for study, and the likelihood of a major renovation or expansion to the plant.
2. Perform laboratory column flotation and selective agglomeration amenability tests on samples collected from the candidate preparation plants in order to determine operating conditions and potential product quality and recovery.
3. Design conceptual plants integrating the advanced flotation and selective agglomeration technologies into the existing plants, and project the capital and operating cost for the additional production from the integrated plants. From these data, present recommendations to the DOE and the coal company for pilot scale testing.
4. Confirm laboratory projections by continuous pilot-scale testing of the recommended application at the selected host preparation plant. Also, further optimize process conditions to obtain design parameters so that the coal company may assess feasibility of a plant conversion to the advanced cleaning process.
5. Determine dewatering, CWF preparation, and briquetting properties of fine clean coal from the pilot operation so that the marketing prospects of the additional coal can be included in the commercialization assessment.

As indicated earlier, accomplishment of the Task 3 objectives was a team effort of Amax Coal Company (later to become part of Cyprus Amax Coal Company), Amax R&D (and later Entech Global), Bechtel, CAER, Arcanum and CCMP. The laboratory testing was done at Amax R&D, CAER, Arcanum and CCMP. Cannelton Coal Company, an operating unit of Cyprus Amax, was responsible for installation of the pilot-scale equipment at the host-site, and CCMP operated the pilot equipment and provided on-site technical direction for testing at the Lady Dunn Preparation Plant host-site in West Virginia. Filtration tests were conducted by Westech, and continuous centrifuge dewatering tests were conducted by DOE/FETC, Pittsburgh. TraDet performed the continuous briquetting tests.

ADVANCED PHYSICAL FINE COAL CLEANING TECHNOLOGIES

The two physical fine-coal cleaning technologies being developed for production of premium fuel are advanced froth flotation (specifically, column flotation) and selective agglomeration.

Column flotation differs from the more common mechanical-cell flotation by usually being accomplished in a single deep tank (or column) rather than in a series of shallower mechanically agitated tanks. In each case the tanks are aerated, but dispersion of the air is often thought to be better in the deeper column system because of the differences in the manner in which the air is introduced into the slurry. The more important difference between the two types of flotation, though, is the capability of adding rinse water effectively to the top of the column. This water, flowing counter-current to the clean coal, washes entrained and adventitious non-floating material from the froth and has the same effect as adding multiple stages of cleaner flotation to a mechanical-cell system. The value of column flotation for separating fine coal from refuse has been described in published accounts [3, 4] and demonstrated by the laboratory and bench-scale testing accomplished during this project to produce premium fuel from finely ground coal [5, 6].

Selective agglomeration cleaning is accomplished by coating particles of fine coal with droplets of an oily bridging liquid under a high-shear mixing regime. Continued mixing encourages the oiled particles to stick together and grow into larger pellets which can be separated from the fine waste by screening or by froth flotation. The procedure is noteworthy for its efficiency – the recovery of fine carbonaceous material by selective agglomeration is often better than by froth flotation alone. Various types of bridging liquids can be used [7]. Volatile liquids such as pentane and heptane are thought to be particularly advantageous from a economic viewpoint since these liquids can be recovered for reuse [7]. On the other hand, one can get by with smaller quantities of oils such as diesel fuel for the agglomeration, and the design of integrated production circuits utilizing low-volatility oils is much simpler. Agglomeration of fine coal with diesel fuel bridging liquid has been described in published literature [8], and laboratory and bench-scale agglomeration with pentane and heptane to produce premium fuel was described in two topical reports of the current project [9, 10]. Because the technology for recycling volatile bridging liquids has not been developed beyond the bench-scale, only the use of diesel fuel, kerosene and heating oil were considered for near-term applications during this task.

POTENTIAL LOCATIONS FOR NEAR-TERM APPLICATIONS

At the time that work began on Task 3 during late 1992, Amax Coal Company operated preparation plants at nine locations, two in Illinois, four in Indiana and three in West Virginia. The plants ranged in age from recent start-ups to original construction decades ago. Despite their wide differences in age, capacities and flowsheets, each of these plants was a typical representative of the preparation plants in their region.

As a first step in identifying potential applications, Amax Coal Company management was asked to suggest candidate sites which could use new technology for improving plant performance. After considering performance records and plans for future production, the Midwest Division (Illinois and Indiana) technical management recommended that the task focus on the Ayrshire Plant and the Cannelton Division (West Virginia) recommended that the task focus on the Lady Dunn Plant. Sometime later, when it was learned that the Ayrshire Mine would be closing, the Midwest Division asked that the Wabash Plant also be considered as a study site for the near-term application.

Amax R&D and Bechtel engineers visited each of the sites to assess their suitability as host sites for the eventual pilot-scale testing. At the same time, the Amax R&D engineers arranged for collection of fine coal slurry samples for laboratory amenability tests, and Bechtel engineers arranged to obtain the existing plant layout and operating data that they would need for the conceptual design and economic feasibility studies.

The specific near-term applications for each of the three preparation plants are described in the following sections.

Ayrshire Preparation Plant

The Ayrshire Mine and Preparation Plant was near Chandler, Indiana and produced surface mined coal from the Indiana VI seam. The preparation plant was a 1,200 st/hr jigging operation originally placed into service in 1973. The minus 28-mesh underflow from the clean coal dewatering screens was cycloned, and the cyclone overflow discarded to a slurry pond (Figure 4). The cyclone underflow was dewatered with EBW basket centrifuges and combined with the clean coal from the jig plant. A significant amount of clean coal was lost in the cyclone overflow, and the quality of the overall plant production was degraded by the excessive amounts of moisture and ash retained in the EBW centrifuge cake. Product quality was an important consideration at Ayrshire since low sulfur coals were being purchased at the time to blend with the plant production in order to meet customer specifications.

The main focus of the near-term application was the 80 tons per hour (dry basis) of fine refuse going to the slurry pond. It was viewed as a potential source of low sulfur coal which could replace some of the coal being purchased as blending stock. In addition some attention was give to improving the quality of the EBW centrifuge cake, perhaps by including a grinding step ahead of advanced cleaning. Samples of each stream were collected for analyses and the laboratory amenability testing discussed in this report.

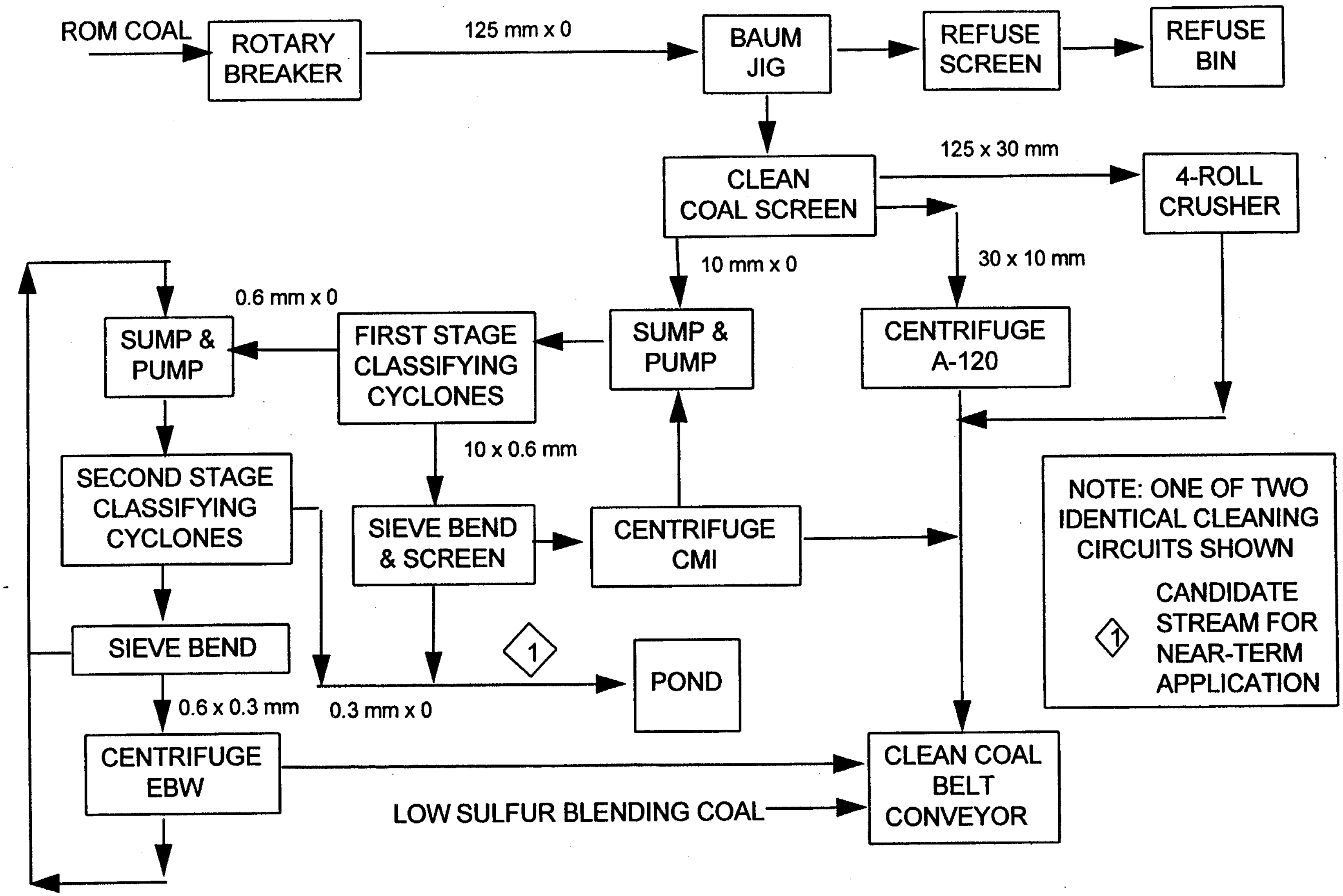

Figure 4. Ayrshire Preparation Plant Flowsheet

Lady Dunn Preparation Plant

The Lady Dunn Preparation Plant located on the Kanawha River east of Charleston, West Virginia received Stockton and Eagle seam coal from a nearby underground mine. The plant had a heavy-media vessel/shaking table/mechanical-cell flotation circuit with a capacity of 550 st/hr at the time the task began in 1992. A multiphase expansion to 1200 st/hr, involving the addition of heavy-media cyclones to the circuit and replacement of shaking tables with spiral separators, was on the planning board at the time (Figure 5).

An evaluation of the plant operation indicated that very likely the Lady Dunn plant could benefit from the use of an advanced cleaning technology to treat the additional fines that would be available when the expansion is completed. Since the plant was being expanded anyway, the advanced cleaning units could be easily incorporated into the circuit if found to be beneficial. In addition to production of a larger quantity and a better quality clean coal for steam coal customers, the advanced technology could also produce low-sulfur special fuels from the coal being mined at the property. Manufacture of coal briquettes as a premium stoker fuel for industrial boilers would be a particularly attractive option. Other options would be the sale of the clean coal as a powder fuel or as coal water slurry fuel (CWF).

The overflow stream from the classifying cyclones in the expanded plant (Figure 5) was identified as a candidate for treatment by the advanced technology. The overflow was expected to contain 35 tons of dry solids per hour. At the time, plant management envisaged installation of additional mechanical flotation cells to clean this stream. Based upon past experience, they expected to achieve about 50 percent recovery, at most, of the combustible material in the cyclone overflow. Since cyclone overflow from the expanded plant would not be available for some time, drum-lot sample of the Vorsiv underflow slurry feeding the existing mechanical-cell flotation circuit was collected for analyses and for the laboratory amenability testing discussed in this report. Since the contemplated feed to the expanded plant also included streams of coarser material than the minus 48-mesh Vorsiv product, a raw coal sample was also collected that could be screened later to make a 28x100-mesh fraction for separate testing.

Wabash Preparation Plant

The Wabash Mine and Preparation Plant near Keensburg, Illinois produced coal from an underground mine in the Illinois No. 5 seam. The preparation plant was a 1,500-st/hr heavy-media-vessel/heavy-media-cyclone operation (Figure 6) that had been placed into service a few months earlier. The minus 1-mm fines from the heavy-media cyclone feed were cycloned with the plus 0.15-mm oversize going to spiral separators and the minus 0.15-mm overflow going to the refuse thickener and disposal. It was this stream, combined with some smaller-volume streams from the dewatering and spiral circuits, that was proposed as a candidate for advanced cleaning since coal recovered there would increase the overall production of saleable coal from the mine. Recent test

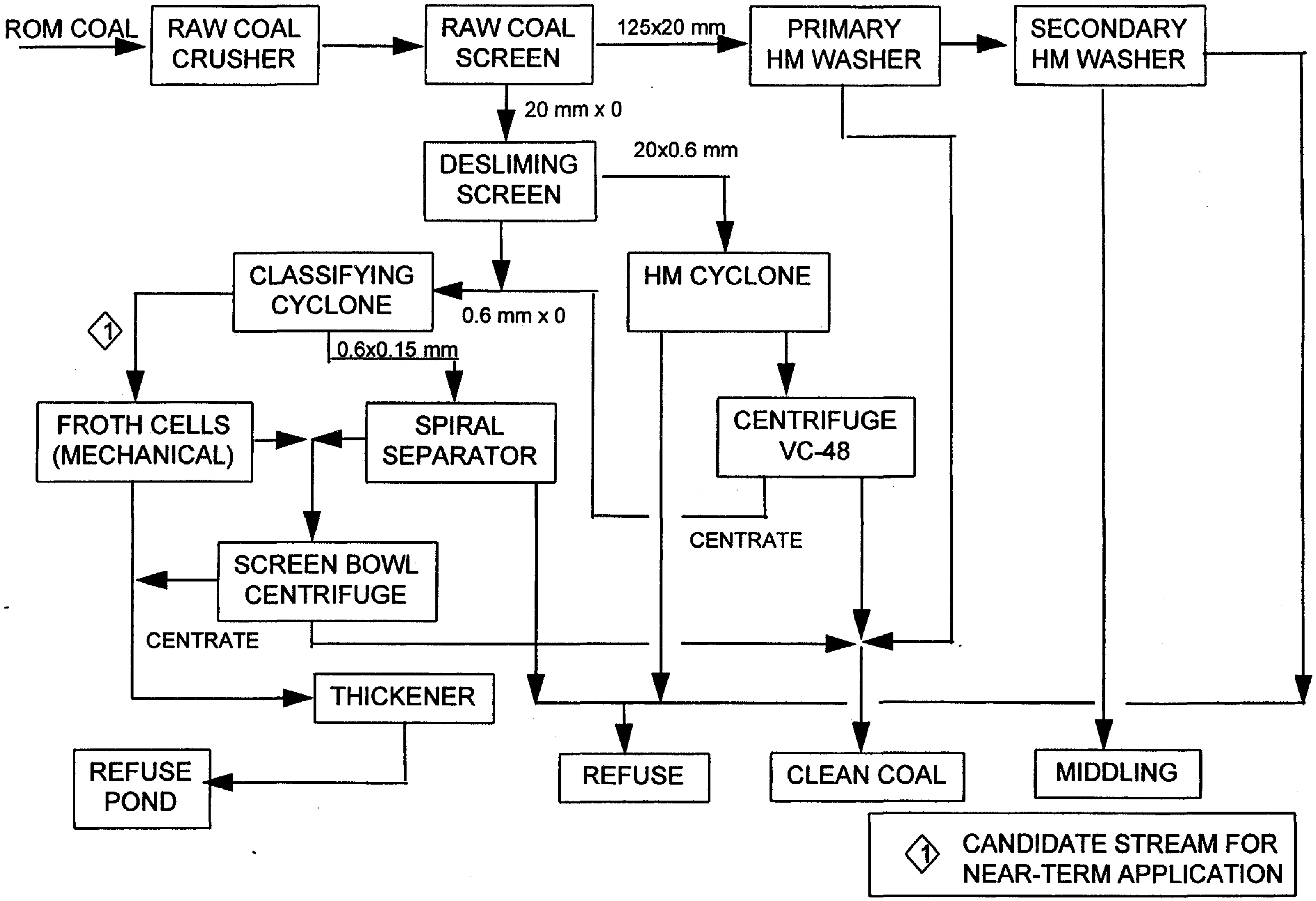

Figure 5. Lady Dunn Preparation Plant Flowsheet

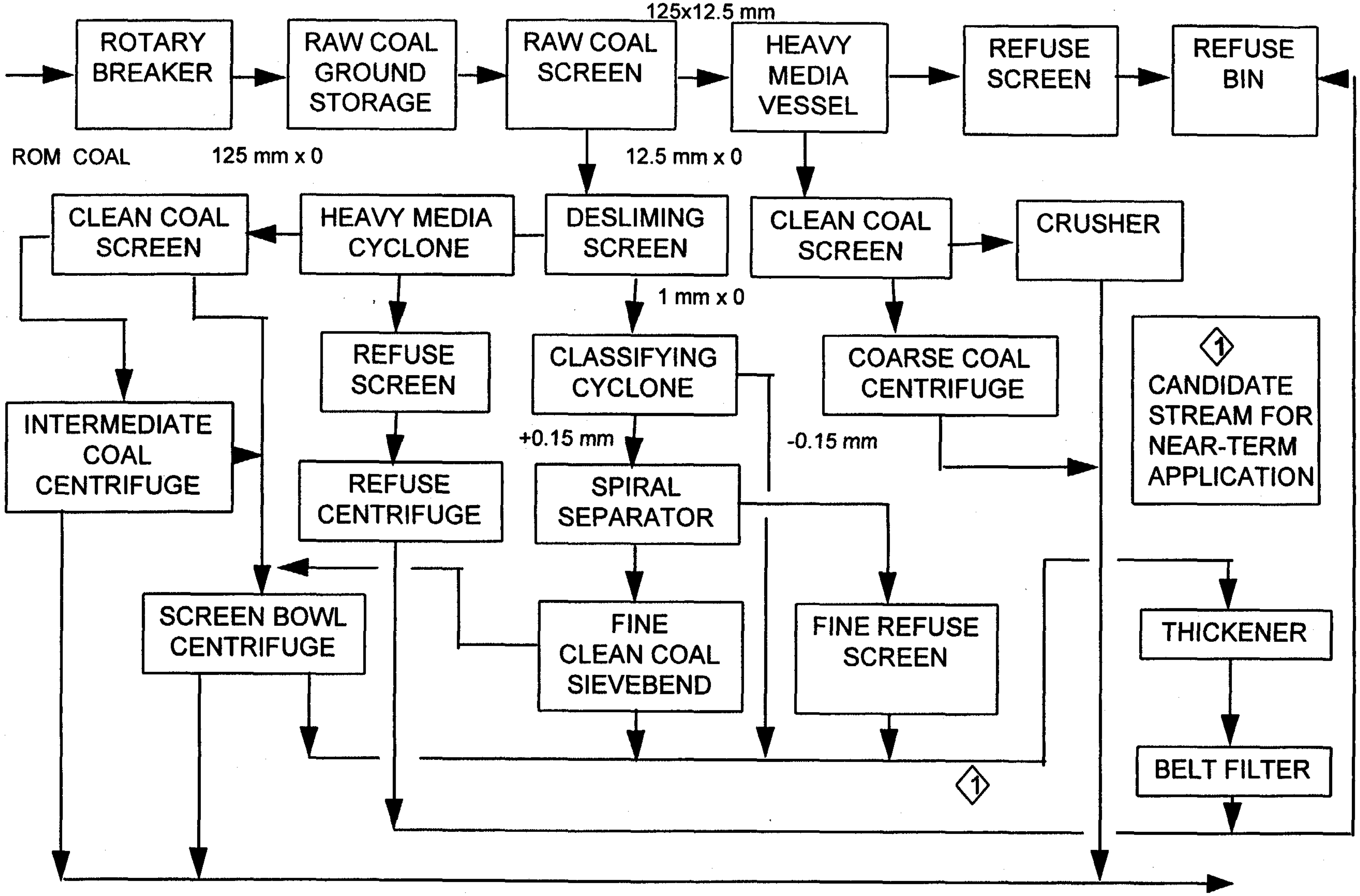

Figure 6. Wabash Preparation Plant Flowsheet

data developed to support an unfunded Clean Coal Technology V submission were available in the coal company files so it was not necessary to obtain new samples from the preparation plant for testing.

LABORATORY AMENABILITY TESTING

Portions of the slurry samples were distributed to Amax R&D, CAER, and Arcanum for the initial amenability testing. A second sample of the Lady Dunn flotation feed slurry was collected at a later date and tested at CCMP to confirm the earlier observations at Amax R&D and CAER.

Sample Properties

The properties of the slurry and centrifuge cake samples that were received at Amax R&D are summarized in Table 2. Some of the water had been decanted from the slurry samples before they were shipped to Amax R&D and CAER.

Table 2. Properties of Laboratory Study Samples

	Ayrshire		Lady Dunn		Wabash
	Fine Refuse	Centrifuge	Vorsiv U'flow	28x100m	-65m Fines[a]
Slurry, % solids	11.0		4.0		3.8 (projected)
Proximate, % dry:					
Ash	64.47	26.79	34.39	30.56	23.90
Volatile Matter	14.58	30.70	21.89	25.51	24.56
Fixed Carbon	20.95	42.51	43.73	43.93	51.54
Sulfur, % dry:					
Total	1.26	2.93	0.67	0.85	1.92
Pyrite	1.02	2.09	0.27	0.14	1.38
Sulfate	0.022	0.045	0.002	0.002	
Heating Value, Btu/lb:					
As Received	681	7,878	1,847	9,939	
Dry	4,508	10,327	9,396	10,045	
Sulfur, lb SO_2/MBtu	5.59	5.67	1.50	1.78	
Particle Size, wt %:					
Passing 14 mesh	100.0	>90.0			
Passing 28 mesh	98.8	65.5	100.0	100.0	
Passing 48 mesh	96.3	26.8	>95.0		100.0
Passing 100 mesh	90.6	7.8	83.1	0.0	86.5
Passing 200 mesh	83.3	3.0			67.6
Passing 325 mesh	78.4	1.7	60.4	0.0	

[a] To simulate cyclone overflow

Three-product washability tests were also made on the Ayrshire and Lady Dunn samples. The separations were at specific gravities 1.60 and 1.90 on samples that had been screened at 100 mesh and 325 mesh. Significant amounts of good coal containing less than 11 percent ash were found in each sample, as shown in Tables 3 and 4. There was also significant enrichment of the pyritic sulfur in the 1.90 specific gravity sink products, particularly in the case of the two Ayrshire samples. Further details of the washability testing are provided in Appendix Tables A-1 through A-4.

Table 3. Washability of Ayrshire Fine Refuse and Centrifuge Cake

Specific Gravity		Weight	Product Analyses				SO_2
Sink	Float	Percent	Ash, %	S(t), %	S(py), %	Btu/lb	lb/MBtu
			Fine Refuse Slurry				
	1.60	22.78	6.97	1.43	0.64	13,266	2.16
1.60	1.90	10.38	18.63	0.96	0.46	11,579	1.66
1.90		66.83	88.32	1.30	1.26	705	36.88
Composite Feed		100.00	62.55	1.30	1.04	4,696	5.54
			Centrifuge Cake				
	1.60	69.12	8.79	2.15	1.13	12,781	3.36
1.60	1.90	8.95	34.50	2.87	2.23	8,735	6.57
1.90		21.93	77.21	5.08	4.93	2,255	45.60
Composite Feed		100.00	26.10	2.86	2.06	10,110	5.66

Table 4. Washability of Lady Dunn Vorsiv Underflow and 28x100 Mesh Coal

Specific Gravity		Weight	Product Analyses				SO_2
Sink	Float	Percent	Ash, %	S(t), %	S(py), %	Btu/lb	lb/MBtu
			Vorsiv Underflow				
	1.60	30.69	6.59	0.85	0.09	13,951	1.22
1.60	1.90	3.54	32.21	0.77	0.33	9,585	1.61
1.90		5.35	76.10	1.42	1.31	2,561	11.09
minus 325 mesh		60.43	46.60	0.57	0.29	7,407	1.54
Composite Feed		100.00	35.39	0.71	0.29	9,234	1.54
			28x100 mesh Screened Coal				
	1.60	62.92	10.72	0.85	0.14	13,353	1.27
1.60	1.90	13.66	39.33	0.84	0.42	8,526	1.97
1.90		23.42	78.73	1.22	1.16	2,040	11.96
Composite Feed		100.00	30.56	0.94	0.42	10,044	1.87

Froth Flotation of Ayrshire Products

Batch and continuous-flow laboratory flotation tests were performed on the Ayrshire products to provide a quantitative basis for the Subtask 3.1 engineering feasibility analysis of advanced column flotation at that plant. It was important during this testing to project the likely yield of clean coal and its quality and to obtain operating and plant design data for parameters having an impact on process economics.

Denver Cell Batch Flotation

The first of the batch flotation tests were Denver cell tree-flotation tests to provide release analysis curves as described by Pratten et al. [11]. The specific tree flotation procedure used at Amax R&D was described in a previous topical report [12] for this project. These tests were made on both the fine refuse and the centrifuge cake. A second test was made on the centrifuge cake after it had been ground for 30 minutes to essentially passing 100 mesh since the washability testing indicated significant pyrite locking with the coal in the float fractions.

Release analysis curves for the three tree-flotation tests are shown in Figure 7. The knee of each of the curves was at 90 percent recovery of the higher heating value in the respective samples. At that point, the clean coal from the fine refuse contained 10 percent ash, and the clean coal from the centrifuge cake contained 12 percent ash. Grinding the centrifuge cake shifted the ash content of the resulting clean coal to the left to 8 percent ash. Flotation also reduced the sulfur content of the coal as shown in Figure 8. Cleaning the Ayrshire fine refuse to 10 percent ash reduced the SO_2 emission of the coal down to 3 lb/MBtu. Cleaning also reduced the sulfur emission of the centrifuge cake, but only to about 4 lb of SO_2 per MBtu.

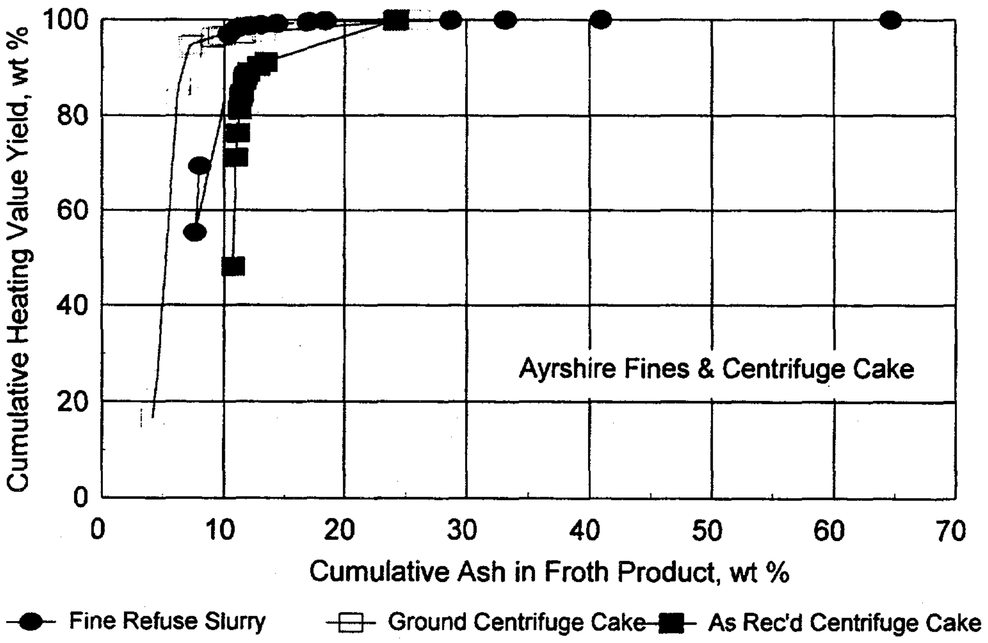

Figure 7. Release Analysis of Ash from Ayrshire Samples

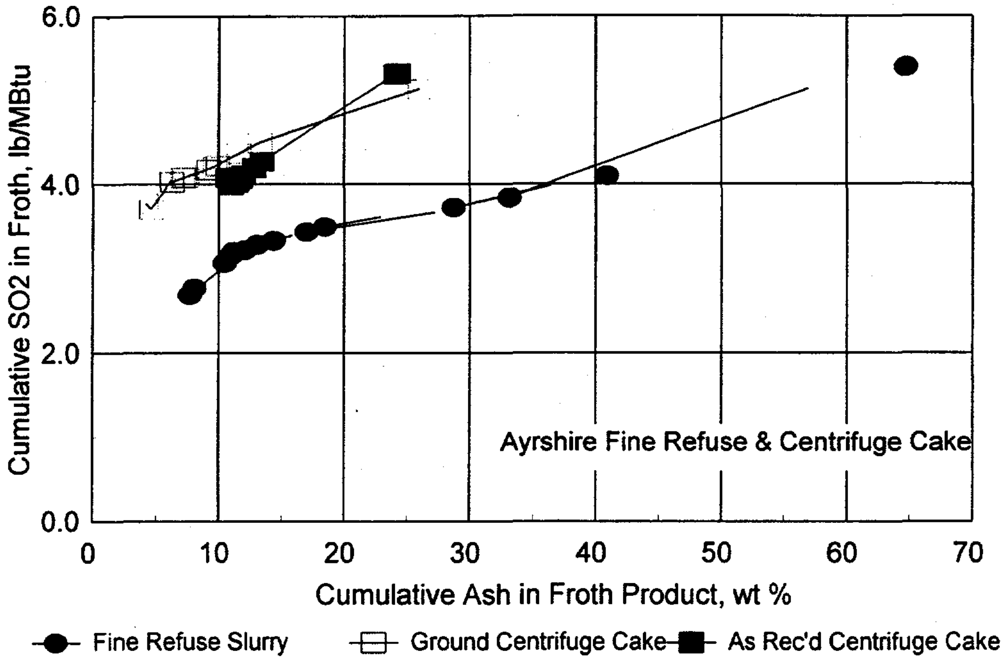

Figure 8. Release Analysis Rejection of Sulfur From Ayrshire Samples

Initial assessments of flotation kinetics and retention times were provided by batch time-recovery tests on the three samples. The time-recovery plots are combined in Figure 9. As one would expect, the trends of the heating value, total sulfur, pyrite sulfur and ash recovery followed each other for each sample. The coal in the centrifuge products (top and center sections of the figure) was faster floating than the coal in the fine refuse (bottom section), taking only 4 minutes to reach maximum yield compared to the 8 minutes for the coal in the refuse. The difference was probably due to the fine particle size of the coal and to the large amount of clay in the refuse slurry. It was also very encouraging to see that the sulfur was slower to float than the coal in the samples.

A rougher-cleaner batch flotation test was performed next on the fine refuse slurry. The flotation time was set at 4 minutes which should produce an 80-percent heating value yield according to the time-recovery tests and 10 percent ash in the clean coal according to the release analysis plot. These results were achieved as shown by the test summary in Table 5. Follow-up tests were subsequently performed to determine the benefits of substituting M-150 glycol frother for the MIBC. These comparison tests were made with two different oil and frother additions and are summarized in Table 6.

It was clearly visible during the tests that M-150 was a more potent frother than MIBC at equal weight additions. It was more persistent during the cleaner flotations and appeared to produce finer bubbles. The performance of M-150 also was less affected by the variations in the amount of diesel fuel added than was the performance of the MIBC frother. As a result, heating value recoveries were greater when using M-150. Unfortunately, the extra coal recovered with the M-150 frother was accompanied by significantly more ash and sulfur than the coal recovered with MIBC.

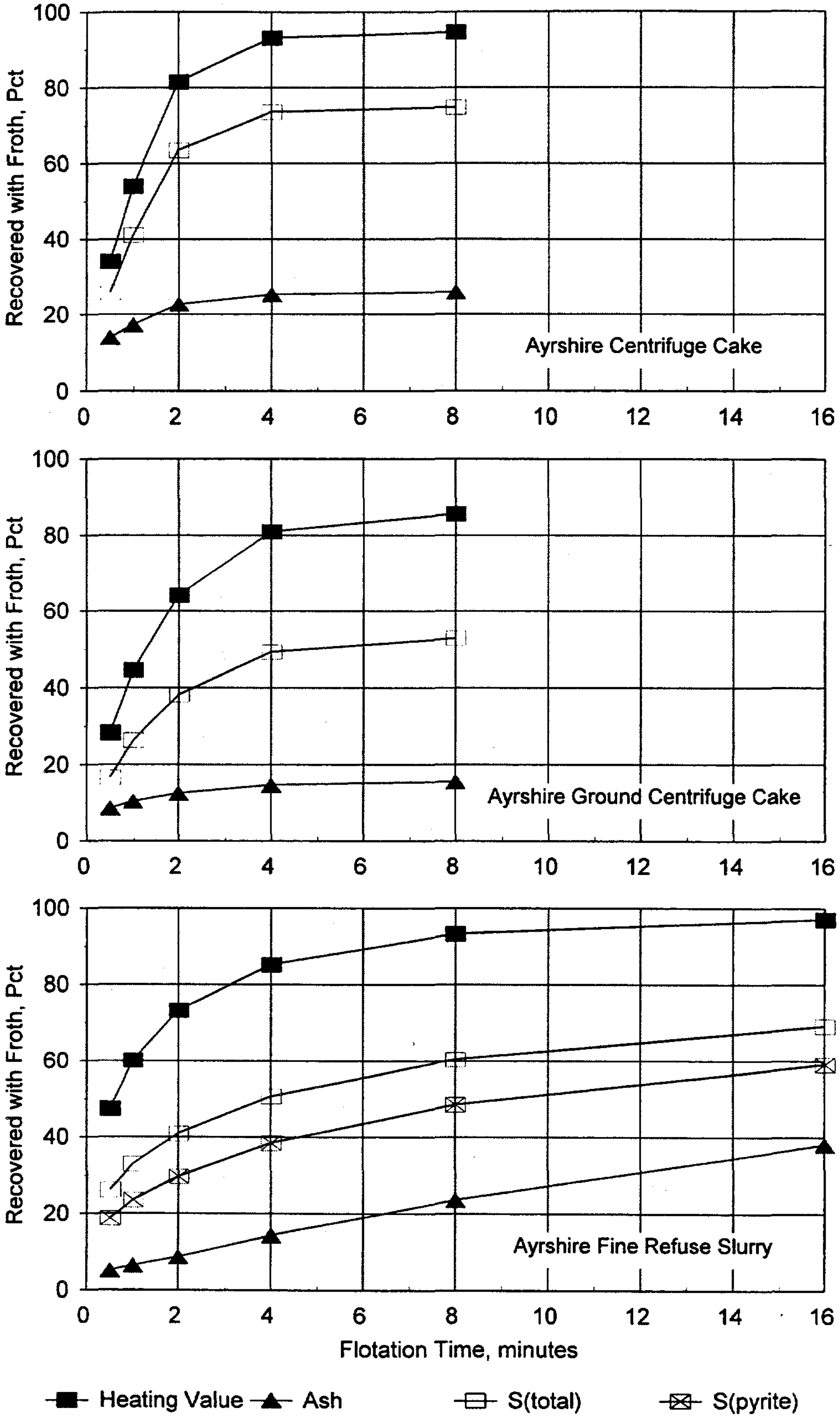

Figure 9. Time-Recovery Flotation of Ayrshire Samples

Table 5. Rougher/Cleaner Flotation of Ayrshire Fine Refuse Slurry

Equipment:	Automated D-12 Denver Cell with 4.4-liter tank
Feed:	Nominally minus 100-mesh refuse slurry containing 351 grams solids diluted to 7.5% solids
Reagents:	1.14 lb MIBC per ton feed 6.42 lb diesel fuel per ton feed
Times:	Rougher - 4 minutes Cleaner - 4 minutes

		Product Analyses				Distribution, Percent				SO_2
Product	Wt, %	Ash, %	S(t),%	S(py), %	HHV, Btu/lb	Ash	S(t)	S(py)	HHV	lb/MBtu
Cleaner Coal	28.00	10.35	1.92	1.22	12,792	4.6	42.4	31.9	78.5	3.00
Cleaner Tail	6.29	89.62	0.73	0.72	329	8.9	3.6	4.2	0.5	44.83
Rougher Tail	65.71	83.46	1.05	1.04	1,461	86.5	54.0	63.9	21.0	14.37
Calc Feed	100.00	63.37	1.27	1.07	4,563	100.0	100.0	100.0	100.0	5.57

Table 6. Ayrshire Fine Refuse Frother Comparison

Reagents, lb/st			2nd Cleaner Results		
MIBC	M-150	Diesel Fuel	Ash, %	S(t), %	HHV Rec, %
1.14	--	8.6	5.65	1.66	41.3
--	1.19	8.8	9.79	2.16	82.5
1.20	--	12.2	7.40	1.92	71.3
--	1.16	11.8	9.86	2.19	83.1

Continuous Column Flotation

CAER performed continuous laboratory flotation tests on the Ayrshire fine refuse using a 2-inch diameter generic Ken-Flote™ column with an internal aeration system [13]. Based upon the results of preliminary scoping tests, a series of parametric tests were conducted on the slurry to investigate the effects of varying aeration, wash water and feed rates on higher heating value (HHV) recovery and the ash content of the clean coal. The slurry was diluted to 10 percent solids for these tests, and 2 lb MIBC frother and 2 lb fuel oil were used per short ton of solids in the slurry. Results of the parametric testing are summarized in Appendix Table A-5.

Figure 10 shows the effect of varying aeration rates on the performance of the column. As one would expect, increasing the aeration increased the heating value recovery. However, the increasing aeration had little impact upon the amount of ash remaining in the clean coal. The best recovery was at 6 standard liters/minute aeration where the HHV recovery was 99.7 percent and the product coal contained 9.96 percent ash. This recovery and product grade agree well with the release analysis plotted in Figure 7.

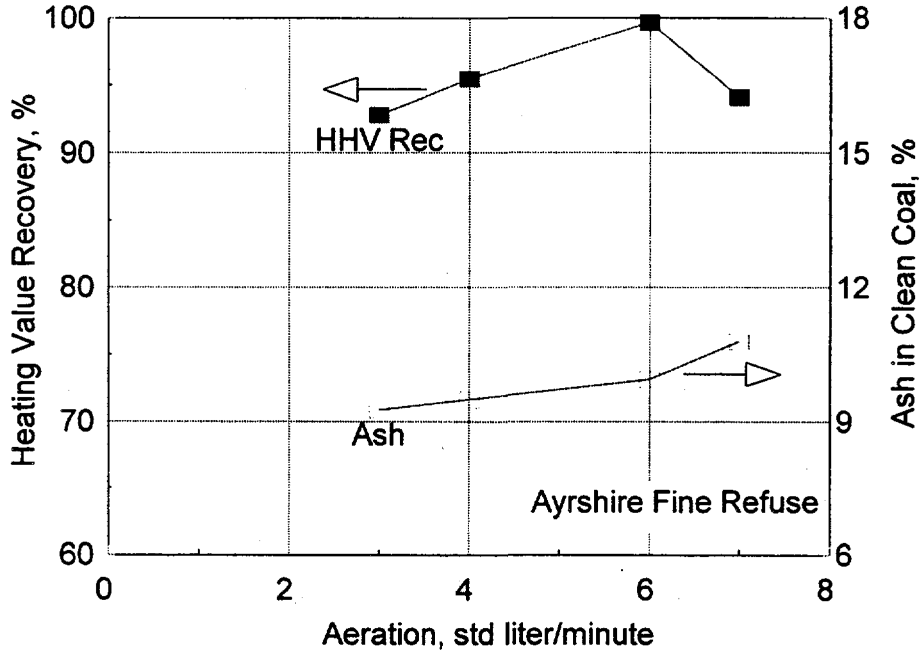

Figure 10. Effect of Aeration Rate on the 2-inch Ken-Flote™ Column Flotation of Ayrshire Fine Refuse Slurry

Operating Conditions: 1.0 liter/minute feed slurry
6.0 kg/hr solids in feed slurry
0.4 liter/minute wash water

The effect of varying the wash water addition is shown in Figure 11. The use of wash water had a significant impact upon the separation. The clean coal contained 17.0

percent ash when no wash water was used and always less than 12.3 percent ash when wash water was used. The best performance was with 0.4 liters/minute wash water where 95 percent HHV recovery was achieved with the resulting clean coal containing 9.5 percent ash.

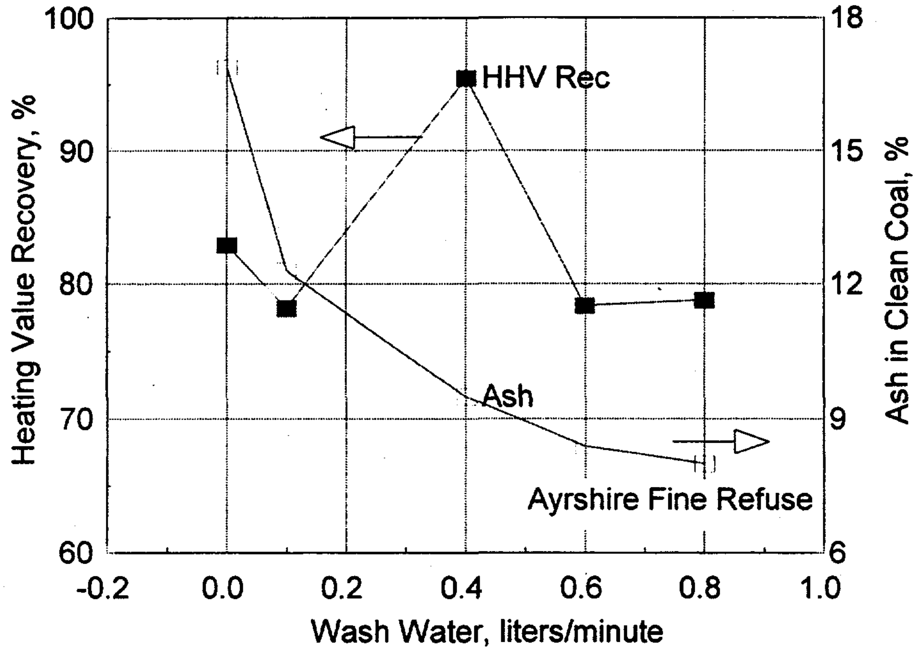

Figure 11. Effect of Wash Water Addition Rate on the 2-inch Ken-Flote™ Column Flotation of Ayrshire Fine Refuse Slurry

Operating Conditions: 1.0 liter/minute feed slurry
6.0 kg/hr solids in feed slurry
4.0 standard liters/minute aeration

Figure 12 shows the effect of varying feed rate on coal recovery and product quality. As the feed rate increased, the heating value recovery declined and the amount of ash in the clean coal increased. The latter effect suggested that the 0.4 liter/minute of wash water added during each of the three tests was not enough to rinse the fine clay thoroughly from the froth when the column was pushed to capacity. It appeared from Figure 12 that 6 kg/hr of solids or 1 liter/minute of feed slurry, which translated into 6 minutes of retention time in the column, was best for this slurry.

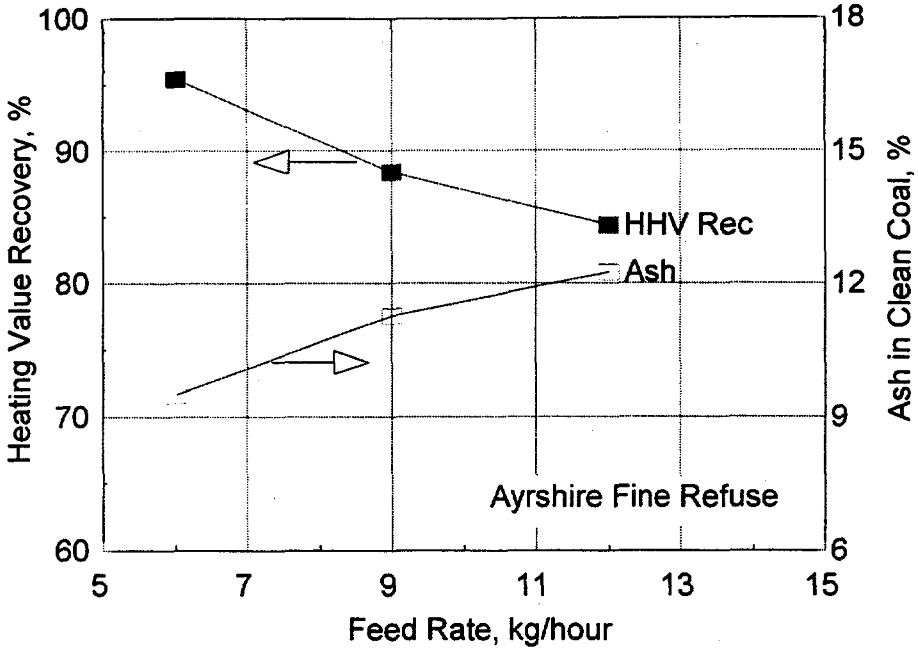

Figure 12. Effect of Feed Rate on the 2-inch Ken-Flote™ Column Flotation of Ayrshire Fine Refuse Slurry

Operating Conditions: 0.4 liter/minute wash water
4.0 standard liters/minute aeration

The consensus of the laboratory flotation tests was that a 10 percent ash product can be prepared from the Ayrshire fine refuse slurry at 95 percent recovery of the heating value in the slurry (or about 80 percent MAF coal recovery). Operating conditions for such a separation in the 2-inch column were 1.0 liter/minute of 10 percent solids feed slurry, 0.4 liter/minute wash water and 4 standard liters/minute aeration.

Selective Agglomeration of Ayrshire Products

Arcanum performed batch laboratory-scale selective agglomeration separations on the Ayrshire products using kerosene and diesel fuel as bridging liquids [14]. Asphalt was mixed with the bridging liquid at times to activate agglomeration and serve as a binder. The batch tests were conducted in a 40-oz Waring blender on 600-ml samples of test slurry. The 600-ml samples were prepared by weighing the proper amount of fine refuse slurry or centrifuge cake into the blender and diluting to the desired solids loading. Bridging liquid was then added to the test slurry and the mixture blended at high speed (12,000 to 18,000 rpm) for 1 minute or until inversion was seen. Blending continued at a slower speed (about 6,000 rpm) for another minute. The small pellets of agglomerated coal which formed during most of the tests were rinsed on a 100-mesh sieve (with 0.15-mm openings) to wash away the dispersed waste material. Only microagglomerates formed when using smaller amounts of bridging liquid. These were collected by flotation in a laboratory Wemco machine with Aerofroth 65 frother.

At least 9.3 percent bridging liquid, on a MAF coal basis, was required to form pellets from the fine refuse that were large enough to be retained on the 100-mesh sieve. However, the microagglomerates which formed when adding 4.5 percent bridging liquid could be recovered by froth flotation. Agglomeration of the fine refuse with kerosene alone resulted in poor phase separation and unsatisfactory yields of screenable material. The addition of 0.2 to 0.4 percent asphalt (based on product weight) to the kerosene improved the agglomeration sufficiently to allow recovery of 85 percent or more of the heating value present in the Ayrshire fine refuse.

The clean agglomeration products contained between 4.24 and 7.53 percent ash, which is lower than the ash content of the column flotation products. Table 7 is a summary of the test results. The ash contents and heating value recovery data in the table have been adjusted to account for the bridging liquid remaining with the coal. Table 7 also contains data for selective agglomeration of centrifuge cake. The agglomerated product recovered from the centrifuge cake by flotation contained 10.23 percent ash. Agglomerated products recovered from the centrifuge cake by screening contained considerably more ash because some of the coarse mineral matter was retained on the test sieve along with the pellets of clean coal.

Table 7. Selective Agglomeration of Ayrshire Fine Refuse and Centrifuge Cake

Feed	Kerosene	Asphalt	Recovery	Clean Coal Product		
% Solids	% of Coal[a]	% of Coal[a]	Method	Ash, %	S(py), %	HHV Rec, %
		Ayrshire Fine Refuse				
4.00	4.50	0.00	Flotation	7.53	0.67	94.5
7.22	5 to 15	0.00	Sieve	Unsatisfactory phase separation		
7.22	5.00[b]	0.00	Sieve	4.24	0.44	19.5
7.22	10.00	0.32	Sieve	5.08	0.52	82.4
7.22	10.92	0.31	Sieve	5.37		94.3
7.22	13.50	0.19	Sieve	4.52	0.64	88.0
7.22	15.75	0.16	Sieve	5.59	0.52	99+
		Ayrshire Centrifuge Cake				
5.00	2.00	0.00	Flotation	10.23	0.98	81.2
18.87	5.00	0.00	Sieve	17.23	1.30	59.8
18.87	10.00	0.00	Sieve	15.96	1.06	66.1
10.00	10.00	0.05	Sieve	16.08	1.08	74.2

[a] Percent of coal on a moisture and ash-free basis

[b] Diesel fuel instead of kerosene

It did not appear from the above results that any further selective agglomeration testing was warranted on the Ayrshire samples. Because of the cost of the bridging liquid, the only combinations which seemed to be at all practical were those with less than 5.0 percent bridging liquid combined with froth flotation for collecting the microagglomerated coal.

Froth Flotation of Lady Dunn Products

Batch and continuous-flow laboratory flotation tests were also performed on the Lady Dunn samples to provide a quantitative basis for the Subtask 3.1 engineering feasibility analysis of near-term applications at that plant. As with the Ayrshire applications, it was important during this testing to project the likely yield of clean coal and its quality and to obtain operating and plant design data for parameters having an impact on process economics.

Denver Cell Batch Flotation

Denver cell tree-flotation tests were run first to provide release analysis curves as described for the Ayrshire samples. These tests were made on both the Vorsiv underflow feeding the mechanical cells in the existing plant and also the 28x100-mesh coal expected to be included with the flotation feed in the expanded plant. A second test was made on the 28x100-mesh coal after it had been ground for 20 minutes to essentially passing 100 mesh since the washability testing indicated significant ash mineral and pyrite locking with the coal in the float fractions.

The release analysis curves for the three tree-flotation tests are shown in Figure 13. The knee of each of the curves was around the 90 percent recovery point of the higher heating value in the respective samples. At that point, the clean coal from the Vorsiv underflow contained 8 percent ash while the clean coal from the unground 28x100-mesh coal contained 13 percent ash. Grinding the 28x100-mesh coal shifted the ash content of the resulting clean coal to the left to about 8 percent ash. Flotation also reduced the sulfur content of the coal somewhat as shown in Figure 14.

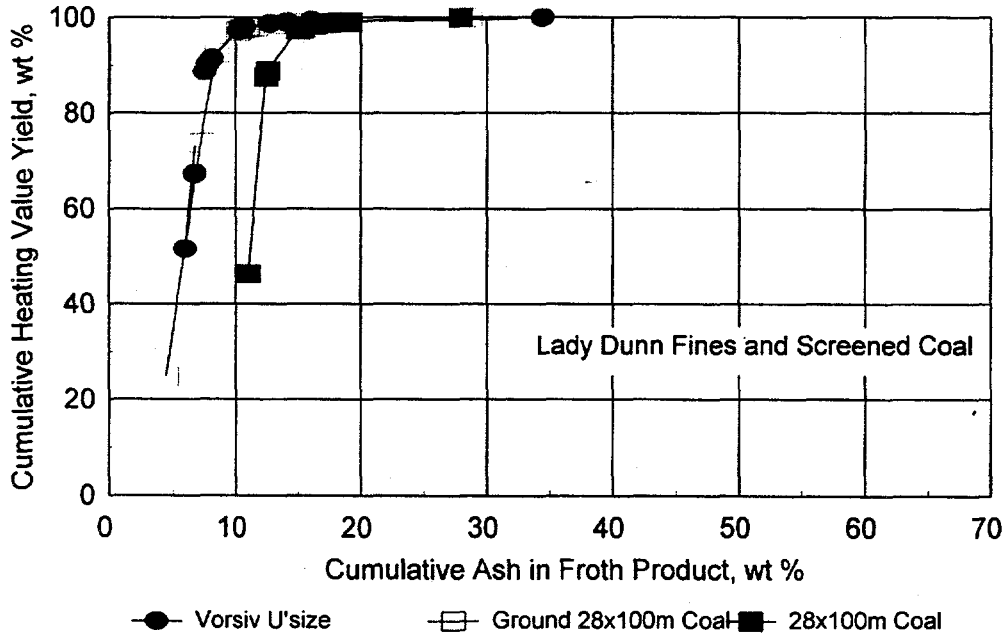

Figure 13. Release Analysis of Ash from Lady Dunn Samples

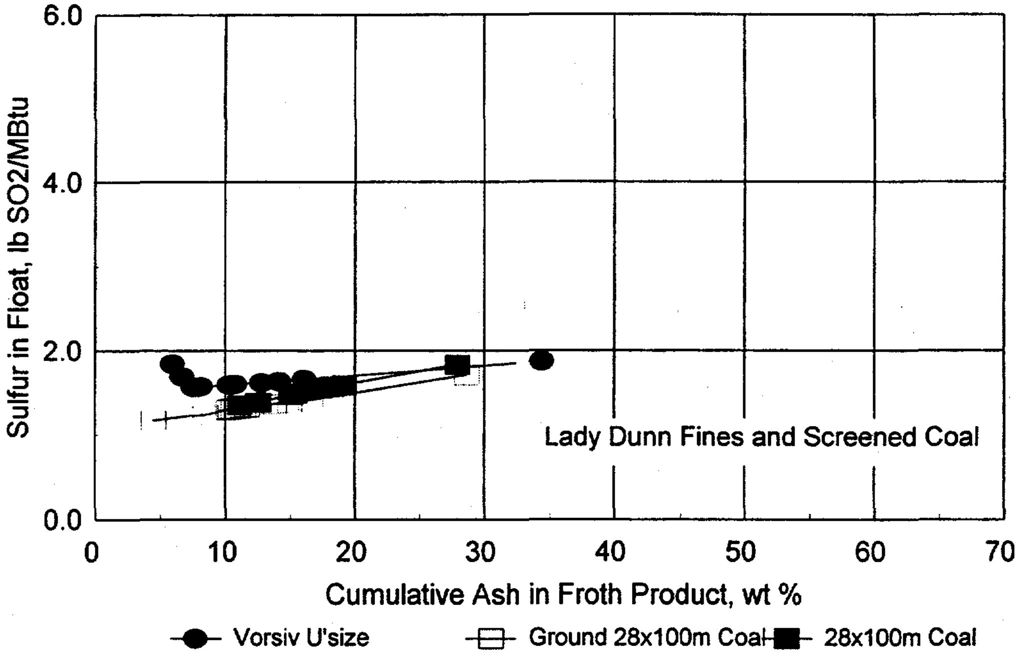

Figure 14. Release Analysis Rejection of Sulfur From Lady Dunn Samples

An initial assessment of flotation kinetics and retention times was provided by batch time-recovery tests on the three products. The time-recovery plots are shown in Figure 15. As one would expect, the trends of the heating value, sulfur and ash recovery from each sample followed each other. The 28x100-mesh coal (top and center section) was faster floating than the coal in the Vorsiv underflow, but flotation was essentially complete after 4 minutes in each case. The Lady Dunn coal did not contain much pyrite so the sulfur distributions followed the coal distributions.

A rougher-cleaner batch test was performed next on the Vorsiv underflow. The flotation time was set at 3 minutes which should produce a 90-percent heating value yield according to the time-recovery tests and 8 percent ash in the clean coal according to the release analysis plot. Actual results fell a little short of these targets as shown by the test summary in Table 8. The use of M-150 glycol frother was also investigated as shown in Table 9. As noted with the Ayrshire fine refuse, M-150 was a more potent frother than the MIBC but tended to pull more ash into the froth along with the clean coal.

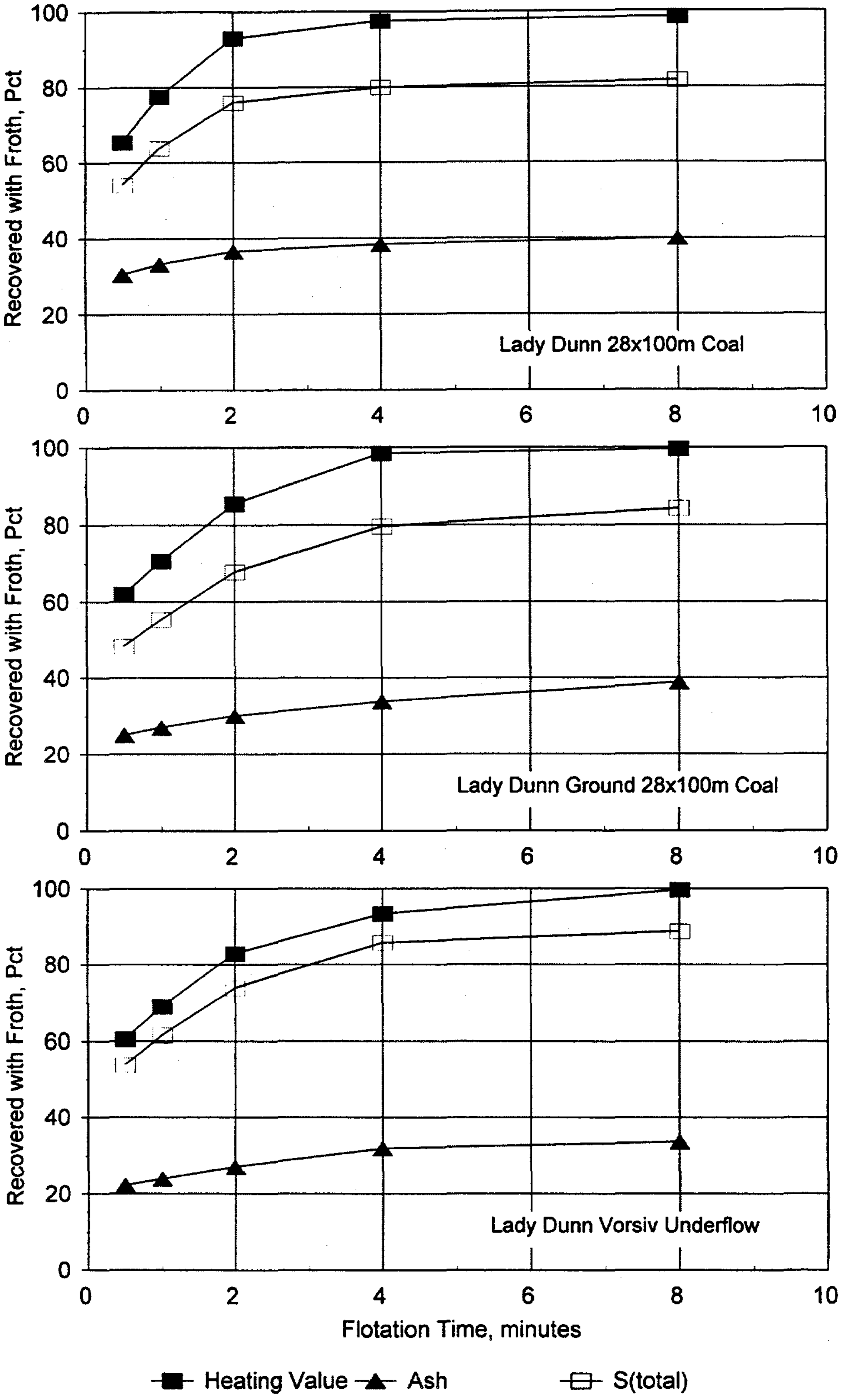

Figure 15. Time-Recovery Flotation of Lady Dunn Samples

Table 8. Rougher/Cleaner Flotation of Lady Dunn Vorsiv Underflow

Equipment:	Automated D-12 Denver Cell with 4.4-liter tank
Feed:	Nominally minus 48-mesh Vorsiv underflow slurry containing 358 grams solids diluted to 7.5% solids
Reagents:	0.84 lb MIBC per ton feed 0.42 lb diesel fuel per ton feed
Times:	Rougher 3 minutes 1st Cleaner 4 minutes 2nd Cleaner 4 1/2 minutes

		Product Analyses				Distribution, Percent				
Product	Wt, %	Ash, %	S(t),%	S(py), %	HHV, Btu/lb	Ash	S(t)	S(py)	HHV	lb/MBtu
2nd Cleaner Coal	55.70	6.81	0.75	0.06	13,954	11.2	58.4	11.7	82.1	1.07
2nd Cleaner Tail	4.12	28.79	0.80	0.30	10,325	3.5	4.6	4.6	4.5	1.21
1st Cleaner Tail	4.51	64.73	0.57	0.42	4,391	8.6	3.6	6.9	2.1	2.60
Rougher Tail	35.67	73.06	0.67	0.58	3,016	76.7	33.4	76.8	11.3	4.44
Calc Feed	100.00	33.96	0.72	0.27	9,471	100.0	100.0	100.0	100.0	1.52

Table 9. Lady Dunn Vorsiv Underflow Frother Comparison

Reagents, lb/st			2nd Cleaner Results		
MIBC	M-150	Diesel Fuel	Ash, %	S(t), %	HHV Rec, %
0.62	--	0.3	4.49	0.72	41.8
--	0.31	0.3	8.61	0.76	80.3
0.84	--	0.4	6.81	0.75	82.1
--	0.41	0.4	10.79	0.78	93.5

Continuous Column Flotation

CAER performed continuous laboratory column flotation tests on the Lady Dunn Vorsiv undersize using the same 2-inch diameter generic Ken-Flote™ column that was used for the Ayrshire fine refuse [13]. Based upon the results of preliminary scoping tests, a series of parametric tests were conducted on the slurry to investigate the effects of varying aeration, wash water and feed rates on higher heating value (HHV) recovery and the ash content of the clean coal. The slurry was diluted to 8.9 percent solids for these tests, and 0.5 lb MIBC frother and 0.5 lb fuel oil were used per short ton of solids in the slurry. Results of the parametric testing are summarized in Appendix Table A-6.

As seen in Figure 16, varying the aeration rate had little impact upon on the recovery of the heating value in the Vorsiv underflow. On the other hand, it did have a significant impact on the amount of ash reporting with the froth. Increasing the aeration rate from 2.0 standard liters/minute up to 5.0 standard liters/minute almost doubled the amount of ash in the clean coal – from 5.4 percent up to 10.4 percent. The results of the two tests at 2.0 and 4.0 standard liters/minute were better than one would expect from the release analyses plotted earlier in Figure 13.

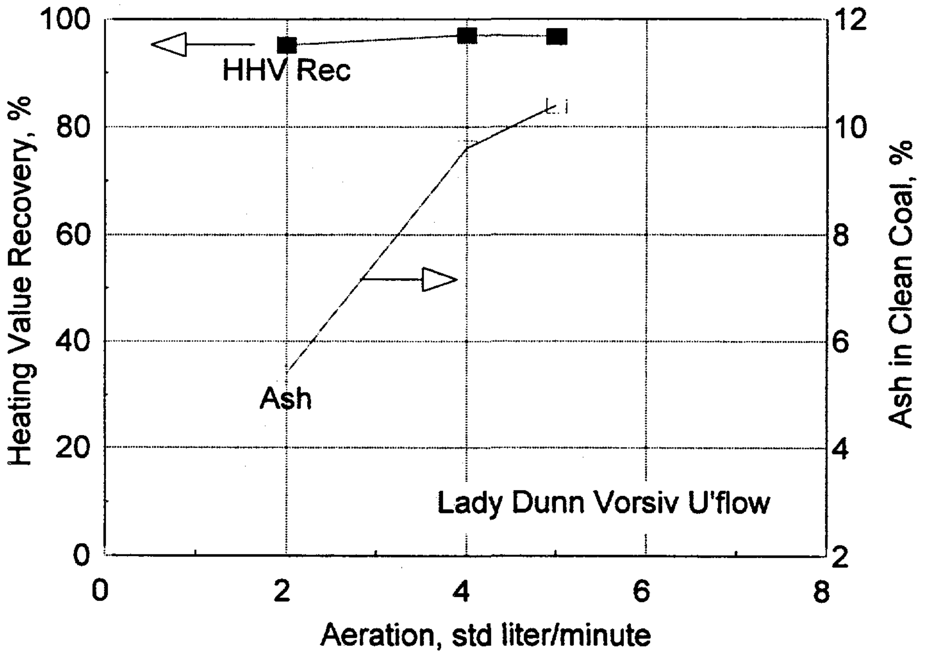

Figure 16. Effect of Aeration Rate on the 2-inch Ken-Flote™ Column Flotation of Lady Dunn Vorsiv Underflow

Operating Conditions: 1.0 liter/minute feed slurry
5.3 kg/hr solids in feed slurry
0.4 liter/minute wash water

The effect of varying the wash water addition is shown in Figure 17. The use of wash water had a significant impact upon the separation. Clean coal recovery declined sharply when 0.6 and 0.8 liters/minute wash water were used, perhaps because of the effect of the extra dilution on the retention time of the slurry in the column. The extra wash water did improve the grade of the clean coal but that would be expected considering the lower recovery. The best performance was with 0.4 liters/minute wash water where 95 percent HHV recovery was achieved with the product containing 9.6 percent ash.

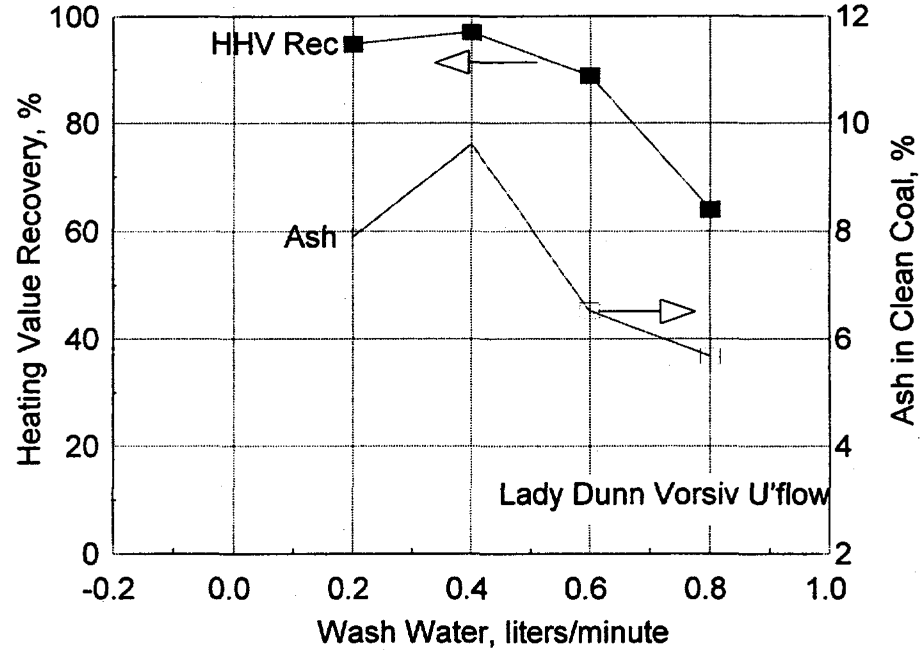

Figure 17. Effect of Wash Water Addition Rate on the 2-inch Ken-Flote™ Column Flotation of Lady Dunn Vorsiv Underflow

Operating Conditions: 1.0 liter/minute feed slurry
5.3 kg/hr solids in feed slurry
4.0 standard liters/minute aeration

Figure 18 shows the effect of varying feed rate on coal recovery and product quality. As the feed rate increased, the heating value recovery declined showing that the carrying capacity of the column was being pushed. It appeared from Figure 18 that 5.3 kg/hr of solids or 1 liter/minute of feed slurry, which translated into 6 minutes of retention time in the column, was best for this slurry.

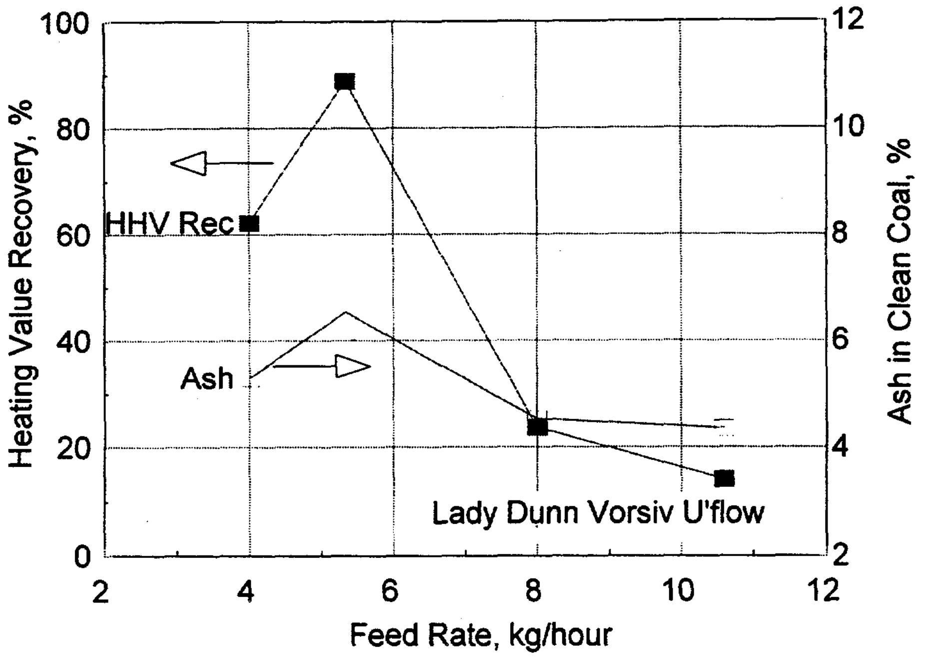

Figure 18. Effect of Feed Rate on the 2-inch Ken-Flote™ Column Flotation of Lady Dunn Vorsiv Underflow

Operating Conditions: 0.6 liters/minute wash water
4.0 standard liters/minute aeration

The consensus of the laboratory flotation tests was that a 6 to 8 percent ash product can be prepared from the Lady Dunn Vorsiv underflow at 95 percent recovery of the heating value in the slurry (or about 90 percent MAF coal recovery). Operating conditions for such a separation in the 2-inch column were 1.0 liter/minute of 8.9 percent solids feed slurry, 0.6 liter/minute wash water and 4 standard liters/minute aeration.

About two years later, after the project team had evaluated the initial laboratory studies described above and found the proposed application to have merit, further laboratory testing was done on the current Lady Dunn flotation feed slurry, a classifying cyclone overflow similar to the Vorsiv underflow described above. These tests were conducted at CCMP in a 2-inch Microcel™ column, the type of column proposed for installation during the plant expansion. The grade-recovery for these tests is plotted in Figure 19. The plot showed 90 percent heating value recovery of coal containing slightly under 10 percent ash. These results generally agree with the previous observations. It was also learned from these tests that a 21-foot column height would be sufficient for this application and that the solids concentration in the feed slurry (6.5 percent) was high enough that the column would not be hydraulically overloaded. In other words, the capacity of a column cleaning this slurry would be limited only by its froth carrying capacity (cross-sectional area) and not by retention time considerations.

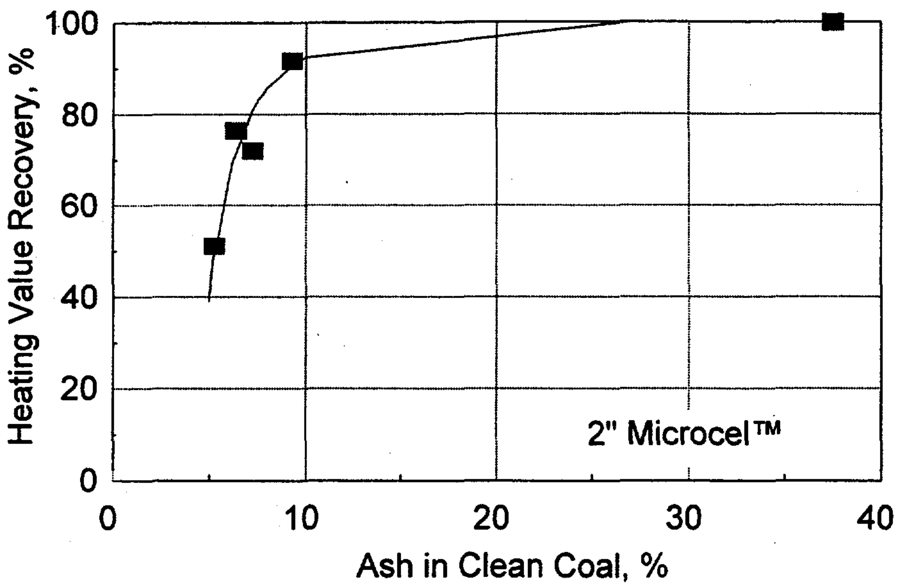

Figure 19. Laboratory Microcel™ Flotation of Lady Dunn Slurry

Selective Agglomeration of Lady Dunn Vorsiv Underflow

Arcanum performed batch laboratory-scale selective agglomeration separations on the Lady Dunn Vorsiv underflow using kerosene and diesel fuel as bridging liquids [14]. The batch tests were conducted in a 40-oz Waring blender on 600-ml samples of test slurry as described for the Ayrshire samples. Between 2 and 15 percent bridging liquid additions were investigated on a MAF coal basis. Froth flotation with Aerofroth 65 was used to recover the microagglomerates formed when using 2 percent bridging liquid. Table 10 is a summary of the test results. The Lady Dunn coal responded to selective agglomeration better than did the Ayrshire coal so it was not necessary to add any asphalt during these tests. The ash content and heating value recovery data listed in the table were adjusted to account for the bridging liquid remaining with the coal.

Table 10. Selective Agglomeration of Lady Dunn Vorsiv Underflow

Feed	Bridging Liquid		Recovery	Clean Coal Product		
% Solids	Type of Oil	% of Coal[a]	Method	Ash, %	S(py), %	HHV Rec, %
5.0	Diesel	2.0	Flotation	7.86	0.12	99.7
7.1	Diesel	5.0	Sieve	4.95	0.06	38.9
15.8	Diesel	5.0	Sieve	6.14	0.09	61.4
15.8	Diesel	5.0	Sieve	6.26	0.11	60.7
7.2	Diesel	10.0	Sieve	5.69	0.08	72.5
15.8	Diesel	10.0	Sieve	7.34	0.13	87.7
5.0	Kerosene	2.0	Flotation	7.30	0.11	98.0
5.0	Kerosene	2.0	Flotation	8.00	0.11	97.1
15.8	Kerosene	5.0	Sieve	6.16	0.15	66.7
15.8	Kerosene	10.0	Sieve	7.47	0.09	89.8

[a] Percent of coal on a moisture and ash-free basis.

It appeared from these results that more diesel fuel bridging liquid would be needed than kerosene if the agglomerates were to be recovered by a screen separation. However, equally good recovery of clean coal was obtained with 2.0 percent diesel fuel and 2.0 percent kerosene when the agglomerated coal was recovered by froth flotation. Over 97 percent of the heating value was recovered for the 2.0 percent bridging liquid froth recovery tests, and the clean coals contained between 7.3 and 8.0 percent ash.

Froth Flotation of Wabash Fines

The decision to include advanced flotation of the natural fines in Illinois No. 5 coal as a near-term application was based upon laboratory and bench-scale testing that had been done a year earlier to support a Clean Coal Technology V submission. One part of that proposal was to install column flotation in the Wabash Preparation Plant in order to recover clean coal from the fines that were rejected by desliming cyclones. The amenability of these fines to froth flotation was demonstrated at CCMP using 2-inch and 8-inch Microcel™ columns. The results of these tests are presented in Table 11. The fine coal responded very well to the column flotation. The rejection of pyrite from the coal, a particularly important consideration at Wabash, was especially noteworthy.

Table 11. Microcel™ Flotation of Minus 65-mesh Wabash Natural Fines

		Analyses, Percent			Distribution, Percent		SO_2
	Weight	Ash	S(t)	S(py)	MAF Wt	S(py)	lb/MBtu
				Test 1 (2-inch Column)			
Clean Coal	69.3	5.03	1.67	0.77	91.4	44.4	2.51
Reject	30.7	79.9	2.19	2.15	8.6	55.6	
Test Feed	100.0	28.1	1.82	1.19	100.0	100.0	
				Test 2 (2-inch Column)			
Clean Coal	44.1	4.44	1.60	0.76	59.3	29.9	2.39
Reject	55.9	48.3	1.86	1.43	40.7	70.1	
Test Feed	100.0	29.0	1.76	1.19	100.0	100.0	
				Test 3 (8-inch Column)			
Clean Coal	44.6	3.80	1.43	0.58	60.2	20.3	2.12
Reject	55.4	48.9	2.29	1.84	39.8	79.7	
Test Feed	100.0	29.0	1.91	1.28	100.0	100.0	

ECONOMIC AND TECHNICAL FEASIBILITY OF PROPOSED APPLICATIONS

After the laboratory studies had shown that both the advanced flotation and the selective agglomeration processes could recover worthwhile amounts of good quality fine coal at each of the three preparation plants, Bechtel performed an engineering feasibility analysis for each application. In other words, Bechtel estimated future production costs in order to determine whether these advanced cleaning technologies could provide coal which would be saleable, at a profit, in the existing market place. They also provided a technical assessment of the risks and benefits of these applications. Details of this study were presented in a Topical Report [2] issued for Subtask 3.1 and are summarized here.

The clean coal produced by the advanced flotation or selective agglomeration may be sold as a wet cake, partially dried cake, dry powder, or in some compacted form at various moisture levels. Marketing conditions will dictate the extent to which the clean coal will have to be processed. Bechtel identified three promising processing and marketing options for cost saving and/or revenue enhancement. These options were:

- Marketing Option A.: Increase the production of clean coal for shipment to existing utility customers by installing advanced fine coal cleaning circuits in the existing preparation plants. The additional clean coal, produced as a centrifuge cake, would be blended directly with the current production of coal.
- Marketing Option B: Production of thermally dried powder fuel for sale separately to special markets. Alternately, the powder fuel may be mixed with current production to reduce the overall moisture content of the coal shipped to the utilities.
- Marketing Option C: Conversion of the thermally dried powder fuel into briquettes for sale separately to special markets.

Since capital charges were expected to be a significant portion of the total production costs for the near-term applications, the first step of the economic and technical feasibility study was to design conceptual site-specific process circuits for each location, that is, the Ayrshire, Lady Dunn and Wabash Preparation Plants. Construction (capital) costs and fixed and variable operating and maintenance (O&M) costs were then derived for each of these circuits to arrive at the total processing cost for each case. There were 15 cases between the three plant locations and the three marketing options as listed in Table 12.

Only column flotation options were included for the Wabash application since the Ayrshire and Lady Dunn application studies had already shown column flotation to be a more attractive application than selective agglomeration.

Table 12. Cleaning and Marketing Options at Near-Term Application Sites

Location	Case	Process	Market Option
Ayrshire Plant	1A	Column Flotation	Blended Centrifuge Cake
Ayrshire Plant	1B	Column Flotation	Dry Powder Fuel
Ayrshire Plant	1C	Column Flotation	Briquettes
Ayrshire Plant	2A	Selective Agglomeration	Blended Centrifuge Cake
Ayrshire Plant	2B	Selective Agglomeration	Dry Powder Fuel
Ayrshire Plant	2C	Selective Agglomeration	Briquettes
Lady Dunn Plant	1A	Column Flotation	Blended Centrifuge Cake
Lady Dunn Plant	1B	Column Flotation	Dry Powder Fuel
Lady Dunn Plant	1C	Column Flotation	Briquettes
Lady Dunn Plant	2A	Selective Agglomeration	Blended Centrifuge Cake
Lady Dunn Plant	2B	Selective Agglomeration	Dry Powder Fuel
Lady Dunn Plant	2C	Selective Agglomeration	Briquettes
Wabash Plant	1A	Column Flotation	Blended Centrifuge Cake
Wabash Plant	1B	Column Flotation	Dry Powder Fuel
Wabash Plant	1C	Column Flotation	Briquettes

Conceptual Design of Proposed Integrated Plants

Table 13 presents a summary of the projected mass balance and performance data for the proposed near-term applications and marketing options. These projections were based on current plant operating data and the future production plans at the three locations and on engineering judgments of the test results described earlier in this report. Tonnages are for an effective operating rate of 3,200 hours per year except for the Wabash drying and briquetting circuits which would operate for 6,600 hours each year. As indicated in the Table, the feed slurries covered a range of pulp dilutions and ash contents, but in each case the clean coals were projected to contain less than 9 percent ash and as little as 4.5 percent ash on a dry basis. Significant reductions in the sulfur contents were also anticipated. The extra clean coal production amounted to 47-52 st/hr and 98.8 st/hr at Ayrshire and Wabash, respectively, since this coal would ordinarily be discarded as waste if not recovered by advanced processing. A portion of the 21-st/hr clean coal production at the Lady Dunn Plant would also be new production since the existing mechanical cells were not very effective for recovering the fine coal at that plant.

Table 13. Projected Plant Performance

		Dry Basis			
	Water, %	Ash, %	S(t), %	HHV Btu/lb	Solids st/hr
Ayrshire Feed Slurry	89.0	45.0	5.5	7,400	100
Column Flotation Product:					
Centrifuge Cake	25.0	9.0	3.1	13,040	47
Dried and Briquetted Products	8.0	9.0	3.1	13,040	47
Selective Agglomeration Product:					
Dewatered Agglomerate	18.0	5.0	3.5	13,620	52.1
Dried and Briquetted Products	8.0	5.0	3.5	13,620	52.1
Lady Dunn Feed Slurry	97.2	35.6	0.9	9,200	35
Column Flotation Product:					
Centrifuge Cake	14.0	8.0	1.3	13,720	21
Dried and Briquetted Products	4.0	8.9	1.3	13,550	43[a]
Selective Agglomeration Product:					
Dewatered Agglomerate	14.0	4.5	1.3	14,290	21
Dried and Briquetted Products	4.0	4.5	1.3	14,290	21
Wabash Feed Slurry	95.9	26.0	1.7	10,415	162
Column Flotation Product:					
Centrifuge Cake	25.0	6.0	1.5	13,694	98.8
Dried and Briquetted Products	8.0	6.0	1.5	13,694	44.9[b]

[a] Includes planned spiral separator clean coal.

[b] Operating 6600 hours/year rather than the 3200 hours/year operated by the flotation plant.

Column Flotation Circuits

Figure 20 is the flow diagram that was proposed for the column flotation circuit at the Lady Dunn Plant [2]. In this case, the feed slurry was overflow from desliming cyclones ahead of spiral separators. An existing screen-bowl centrifuge and a refuse thickener, both with spare capacity, were available to receive the clean coal froth product and fine refuse, respectively. The flow diagrams for the column flotation circuits at Ayrshire and Wabash were similar to the diagram proposed for the circuit at Lady Dunn [2]. New screen-bowl centrifuge capacity was added at the latter locations, though. In all three cases, the existing fine refuse disposal system was utilized for the waste from the new circuits.

The Ayrshire Plant and the Lady Dunn Plant were each fitted with two 10-ft dia by 23-ft high flotation columns set up in parallel circuits. The Wabash plant was fitted with six of the same size flotation columns, also set up for parallel flow.

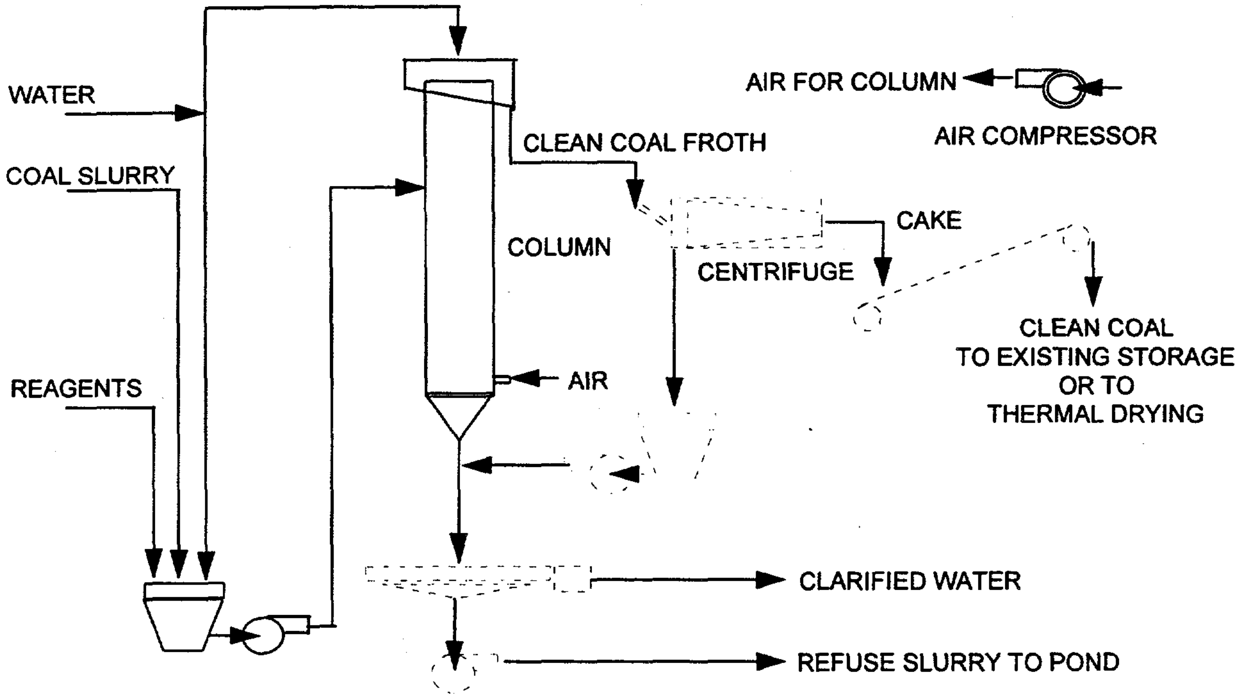

Figure 20. Flow Diagram of Proposed Lady Dunn Column Flotation Circuit
(Existing Equipment Shown as Broken Lines)

Selective Agglomeration Circuits

Figure 21 is the flow diagram that was proposed for the selective agglomeration circuit at the Lady Dunn Plant [2]. An existing thickener was used to thicken the feed slurry. High-shear conditioning with fuel oil bridging liquid was accomplished with a 175-hp mixer. The agglomerates were collected by a gravity separator/skimmer and dewatered in an existing screen-bowl centrifuge. Refuse disposal was through the existing plant system.

The Ayrshire selective agglomeration flow diagram was similar to the Ayrshire flow diagram. As with the proposed column flotation circuit, fine refuse slurry from the existing plant was the feed to the selective agglomeration circuit. This time, though, the feed slurry was thickened to 25 percent solids before cleaning. Agglomeration was accomplished by 500-hp high- and 400-hp low-shear conditioning in series. An intermediate mechanical-cell flotation step was included between the two conditioning steps to collect the microagglomerates and allow dispersed ash minerals to escape. The final-stage agglomerates were collected on static cross-flow screens and dewatered in screen-bowl centrifuges. Refuse disposal was through the existing plant system.

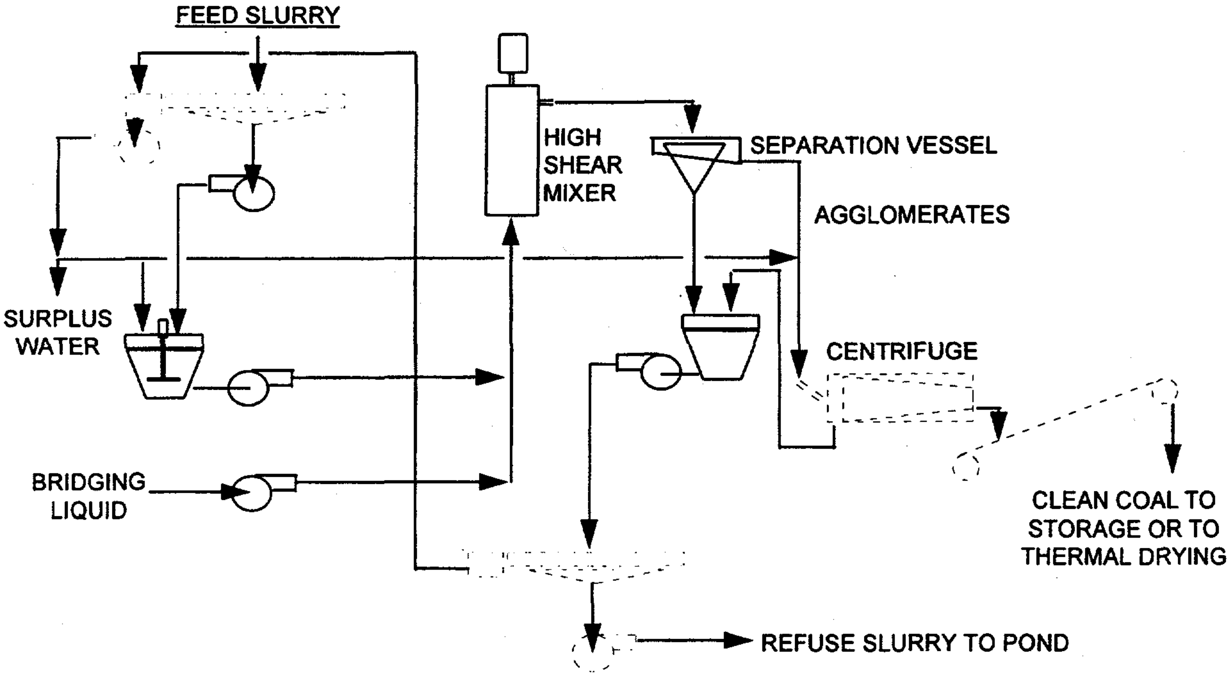

Figure 21. Flow Diagram of Proposed Lady Dunn Selective Agglomeration Circuit
(Existing Equipment Shown as Broken Lines)

Thermal Drying Circuit

Figure 22 is the flow diagram that was proposed for thermally drying the clean coal from the Ayrshire Plant advanced fine coal cleaning circuits [2]. The moisture in the centrifuge cake was evaporated in an entrained flow dryer by the combustion gas from a natural gas burner. The dry product was caught in dust collectors and stored under nitrogen in truck load-out bins. A portion of the exit gas was cooled with a chilled glycol heat exchanger and recycled to provide a portion of the gas flow through the 4.7-ft dia by 100-ft tall dryer. Virtually the same circuit was planned for the Wabash Plant except that the drying circuit operated full time rather than half time and for the Lady Dunn Plant as well except that the equipment was somewhat smaller in size.

Briquetting Circuit

Figure 23 is the flow diagram proposed for briquetting the dry powder coal from the Ayrshire Plant advanced cleaning circuits [2]. This was a simple circuit for briquetting fine coal with a force-feed roll-press compacting machine at approximately 30,000 psi. The design of the circuit was strictly based on Bechtel experience and vendor recommendations since no briquetting tests were performed during Subtask 3.1. The addition of hot liquid asphalt was shown in the diagram as a binder, but other materials could be used as well. The circuit included a product screening step so that the

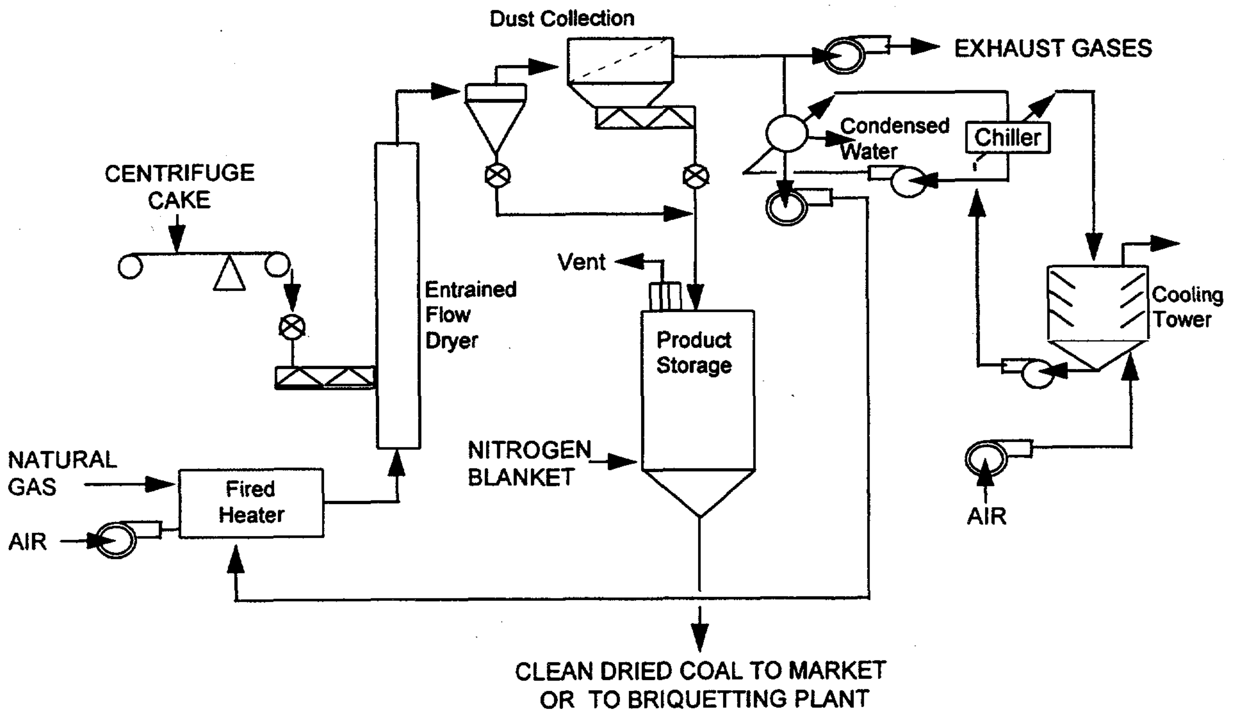

Figure 22. Flow Diagram of Proposed Ayrshire Thermal Drying Circuit

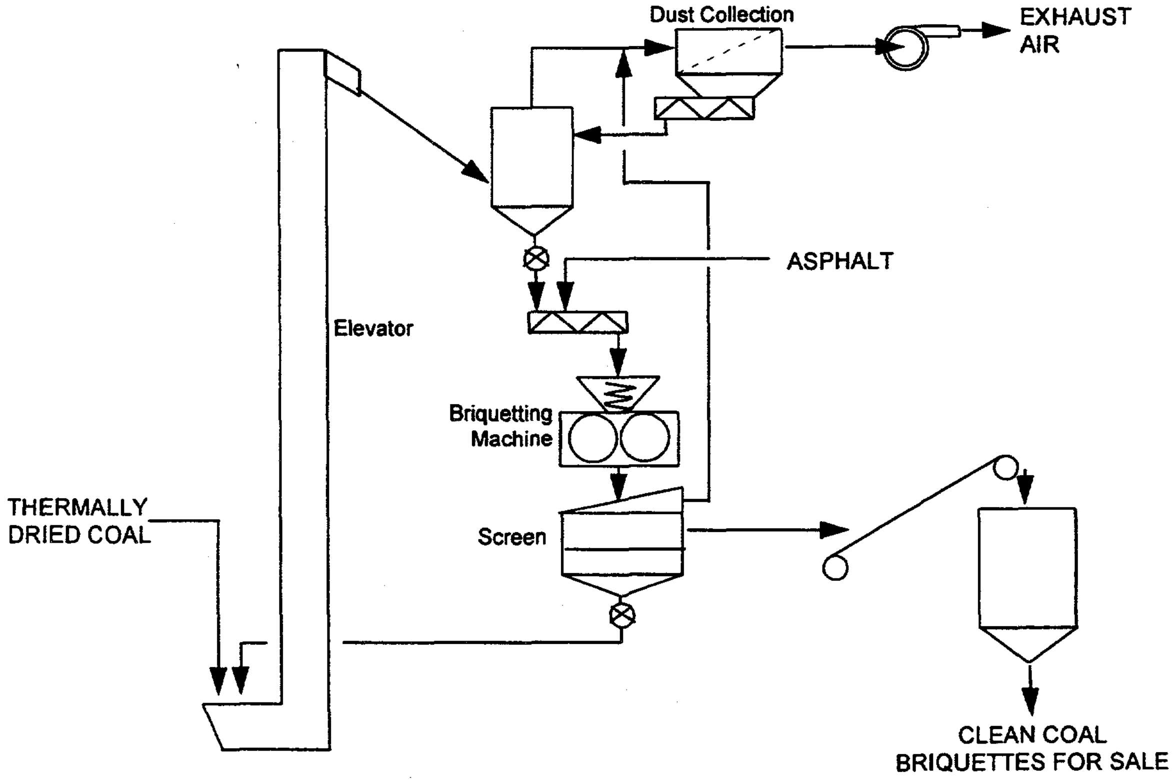

Figure 23. Flow Diagram of Proposed Ayrshire Briquetting Circuit

flashing broken off the briquettes and any fines that by-pass the rolls can be returned to the briquetting machine. Similar briquetting equipment would be used for the dried Lady Dunn and Wabash fine coals.

Economic Comparisons of the Proposed Applications

Capital and operating costs for the column flotation, selective agglomeration, thermal drying and briquetting circuits were estimated separately and combined for the 15 cases considered for the economic comparisons.

Capital Costs

The first estimates were for the site-specific capital costs of each the these circuits as detailed in the Bechtel engineering analysis topical report [2]. Major process equipment and material handling items that would need to be purchased for each case were selected based upon service requirements and mass-balance calculations. Vendor quotes were obtained for these items and appropriate amounts added to the quotes for freight and for installation labor and materials to obtain total installed prices for the major equipment. These equipment lists and prices were included in the topical report [2]. Additional amounts, based upon Bechtel construction experience, were added to the total installed equipment prices to cover the cost of instrumentation, piping, structural steel, electrical, concrete, building finish, excavation, and various indirect and construction overhead accounts to arrive at the total installed cost of each of the circuits.

The total installed costs projected for each location for the advanced cleaning and thermal drying circuits are shown in Table 14. It should be noted that detailed estimates were only prepared for the thermal drying circuits at the Ayrshire Plant. The projected dryer costs at Lady Dunn and Wabash were extrapolated from the Ayrshire circuits after allowing for the differing tonnages, feed and product moistures, and operating schedules at the different locations. The installed costs of briquetting circuits were not estimated separately because there were no test data available from which to base equipment selections. Instead, a combined capital and operating cost figure of $7.26/st ($8.00/metric ton) was used for each of the briquetting estimates. The combined amount is representative of recently published briquetting costs and of Bechtel experience when studying similar projects in the United States.

Table 14. Capital Cost Summary
(millions of dollars, 1993)

	Ayrshire Plant		Lady Dunn Plant		Wabash
	Flotation	Agglomeration	Flotation	Agglomeration	Flotation
Advanced Cleaning	$3.66M	$6.80M	$1.50M	$1.60M	$9.16M
Thermal Drying	5.36M	4.22M	3.4M[a]	1.7M[a]	5.4M[a]
Briquetting	Not Estimated Separately				

[a] Projected from Ayrshire plant cost estimates.

Processing Costs

The Bechtel topical report [2] contained detailed projections of the O&M costs for the advanced cleaning and thermal drying operations. These O&M costs included amounts for all labor, maintenance materials and supplies, operating supplies (flotation reagents, bridging liquids and flocculants), electric power, natural gas and water. Credits were allowed for the reduction in the amount of fine refuse sent to disposal and, in the Ayrshire selective agglomeration case, for a reduction in the water consumption of the integrated plant. An allowance for capital charges was added to the O&M cost to arrive at the total processing cost for the 15 cases cited earlier. The capital charge was based on amortization of the total installed cost of each circuit in equal annual payments over a 25-year plant life at 8 percent interest. As discussed earlier a fixed allowance was used for the combined capital charges and O&M costs for briquetting. The fixed amount for briquetting was reduced somewhat for the Wabash case because of the extra number of operating hours scheduled at that location.

Figure 24 is a comparison of the total processing costs for the 15 cases studied during Subtask 3.1. The comparison is on a dollars per short ton of dry product basis using 1993 prices. Further details are provided in Table 15 and in the Bechtel engineering analysis report [2]. As one would expect, producing centrifuge cake for blending with the current plant production was the lowest-cost option at each location. The cost of producing centrifuge cake after column flotation cleaning ranged from $5.63/st at Lady Dunn up to $8.73/st at Wabash. Column flotation was also less expensive than selective agglomeration at Ayrshire and Lady Dunn, although the difference was only $3.18/st at Lady Dunn. Most of the difference in cost between column flotation and selective agglomeration was due to O&M charges, especially for electric power and the fuel oil used as the bridging liquid. There was a larger difference between the two cleaning costs at Ayrshire because it was more difficult to agglomerate Ayrshire coal than to agglomerate Lady Dunn coal.

Drying added between $7.36/st and $10.65/st to the total processing cost. The high and low end of the range were for drying agglomeration clean coal and flotation clean coal, respectively, at the Ayrshire location. Because of the amount of oil used as the bridging liquid, the centrifuged agglomeration clean coal was expected to contain less residual moisture that would need to be evaporated. As indicated earlier, it was estimated that briquetting would add between $6.17/st and $7.26/st to the processing cost. This led to total processing costs between $24.02/st and $36.06/st for the briquetted clean coal on a bone-dry basis. On a heating value basis, the total processing cost of the briquetted clean coal ranged from $0.84/MBtu for flotation clean coal at Lady Dunn on up to $1.32/MBtu for agglomeration clean coal at Ayrshire (Table 15).

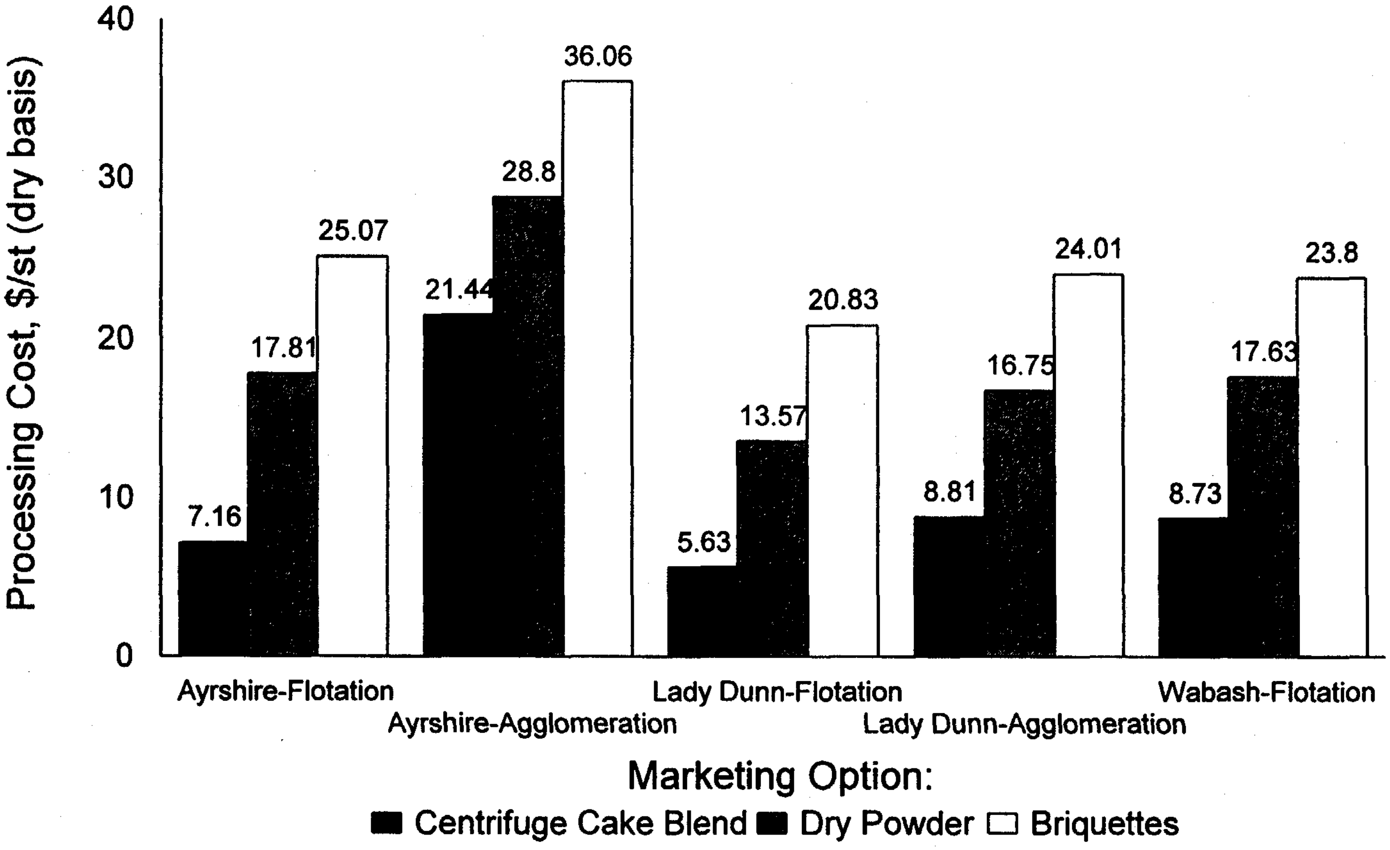

Figure 24. Processing Cost Summary for Plant Location and Marketing Options
(1993 Prices)

Table 15. Processing Cost Summary
(1993 Prices)

	Ayrshire Plant				Lady Dunn Plant				Wabash Plant	
	Flotation		Agglomeration		Flotation		Agglomeration		Flotation	
	$/st	$/MBtu	$/st	$/MBtu	$/st	$/MBtu	$/st	$/MBtu	$/st	$/MBtu
Advanced Cleaning:										
Operating & Maintenance	4.92		17.59		3.59		6.54		5.93	
Capital Charges[a]	2.24		3.85		2.04		2.27		2.90	
Total Advanced Cleaning	**7.16**	**0.27**	**21.44**	**0.78**	**5.63**	**0.21**	**8.81**	**0.31**	**8.73**	**0.32**
Thermal Drying:										
Operating & Maintenance	7.28		4.98		5.57		5.60		7.21	
Capital Charges[a]	3.37		2.38		2.37		2.35		1.69	
Total Thermal Drying	10.65	0.41	7.36	0.27	7.94	0.29	7.95	0.28	8.90	0.33
Cumulative Advanced Cleaning & Thermal Drying	**17.81**	**0.68**	**28.80**	**1.05**	**13.57**	**0.50**	**16.76**	**0.59**	**17.63**	**0.65**
Briquetting:										
Total Briquetting[b]	7.26	0.28	7.26	0.27	7.26	0.27	7.26	0.25	6.17	0.23
Cumulative Advanced Cleaning, Thermal Drying & Briquetting	**25.07**	**0.96**	**36.06**	**1.32**	**22.96**	**0.77**	**24.02**	**0.84**	**23.80**	**0.88**

[a] Capital charges at 8 percent interest over 25 years.

[b] Published data and Bechtel experience for similar plants, breakdown between O&M and capital charges not available.

Discussion of Economic Comparisons

The projected processing costs at the three locations, Ayrshire, Lady Dunn and Wabash, were not really comparable since they reflected differences in site conditions, utility rates and feed material characteristics that were very site specific. For example, the solids content of the feed slurry had a significant effect on the flotation cell volume required per ton of coal processed. It was a major factor affecting the capital and operating costs of the flotation circuits. The required volume of the flotation columns increased as the feed slurry coal and solids content decreased. Feed slurry solid contents at Ayrshire, Wabash and Lady Dunn were 11.0, 4.2 and 2.8 percent, respectively. Thus, the Ayrshire Plant, which processed the slurry with the highest solids content, had the lowest flotation volume per ton of coal.

Flotation and agglomeration characteristics of the coal were other factors which affected processing costs. The Ayrshire fine refuse coal had poor flotation properties and required approximately 5 minutes of retention time versus the 3.5 minutes required by the other two coals. The Ayrshire coal also had poorer agglomeration properties than the Lady Dunn coal, this difference meant that extra shearing/mixing time was needed which consumed a significant amount of extra electrical energy. Twice as much bridging liquid was also required for agglomerating the coal in the Ayrshire fine refuse. These were some of the reasons that the Ayrshire applications were less attractive cost-wise than the Lady Dunn and Wabash applications.

Screen-bowl centrifuges for dewatering the fine coal accounted for a major part of the capital charges. Unlike the Ayrshire and Wabash locations, the Lady Dunn Plant had spare centrifuge capacity, and spare thickener capacity as well, for use with the column flotation and selective agglomeration circuits. This was part of the reason that the Lady Dunn applications tended to be more attractive than similar applications at the other two plants. On the other hand, the Wabash column flotation application benefited from the larger scale of the operation, particularly with respect to the drying and briquetting circuits.

These processing cost projections can be refined by further testing and process development, particularly in the drying and briquetting areas. For instance, the chiller for cooling the recycle combustion gas was a major consumer of electric power in the drying plant conceived for this study. An evaluation of the cost of using nitrogen or carbon dioxide, or even flue gas from an outside source, as a replacement for the recycle gas would be of interest. Similarly a better definition of briquetting costs would be possible if test data were available, particularly for elevated-temperature, high-pressure binderless briquetting, since binder costs were a large part of the generic briquetting cost used for the study.

Technical Assessment

This section presents a discussion of the technical risks and benefits of the processing options studied during the engineering analysis subtask. The three distinct processing options which will be considered separately are 1) the fine coal cleaning, 2) the thermal drying, and 3) the briquetting. The discussion is largely taken from the 1993 Bechtel engineering analysis technical report [2].

Technical Risks in Column Flotation and Selective Agglomeration

For coal cleaning plants, major issues to be considered in an analysis of technical risk are a) the characteristics of the feed coals and b) the characteristics of the process and its efficiency for producing the expected amount and quality of product. Further, the combined characteristics of the feed coal and the process affect the plant design parameters used to develop capital and O&M cost estimates. These design parameters influence the number and type of equipment required and their capital costs, as well as elements of O&M costs such as reagent consumption and power requirements.

Coal Characteristics: The characteristics of the feed coal play a vital part in determining the quality and the quantity of clean coal produced in a preparation plant. The column flotation and selective agglomeration circuits included in this study used streams from existing coal cleaning plants as feed stock. Unlike new plants designed to process coals from beds that have not yet been fully developed, the plant circuits proposed for this study will not face risks associated with unfamiliar feed material. Future supplies of feed coal will be derived from areas close to the areas currently being mined, so possible variations in coal quality can be projected with some certainty for future years.

Laboratory, bench and pilot scale tests on representative samples from the proposed preparation plants can be used to validate coal-related design parameters. These parameters include:

- Quality of the feed and clean coal
- Percentage yield of clean coal
- Retention time required for column flotation and selective agglomeration
- Reagent/bridging liquid consumption
- Dewatering characteristics of the products, appropriate equipment, and expected moisture content of the dewatered product
- Flow characteristics of the dewatered product

Dewatering operations for clean coal and tailing/refuse are a major component of capital and operating costs for coal preparation plants. Evaluation of the dewatering characteristic of the product coal is important as it affects not only the type of equipment suitable for the duty and its cost, but also the residual moisture in the product. A higher than expected moisture level in the dewatered coal will severely limit the amount of the fine coal that can be blended with the current production of clean coal without exceeding contract stipulations for the heating value and moisture content of the shipments. Also, a higher moisture content will increase operating costs if the product has to be thermally dried.

Dewatering or filtering characteristics of the refuse from the fine coal cleaning systems are a vital concern for preparation plants which dewater/filter the fine refuse for disposal in solid form. Both the Ayrshire and the Lady Dunn Plants pumped their fine refuse to disposal ponds as slurry without dewatering. On the other hand, the fine refuse from the Wabash Plant was thickened and dewatered in belt filters before disposal. Belt filters are especially well suited to handle fine slurries with high ash contents. With the installation of column flotation units, the quantity of refuse to be handled by the thickener and belt filter will decrease. It is expected that the existing thickener and filter at the Wabash Plant will be more than adequate for the reject slurry from column flotation.

Testing the flow properties of the dewatered coal should be a part of the product characterization tests, as flow properties have a significant impact on the design of handling and drying systems. Moisture content and particle size are some of the most important factors affecting coal flow properties. In particular, the flow properties of the clean coal agglomerates have to be evaluated as industrial experience with this material is limited.

Process Characteristics: Even though column flotation technology has been applied commercially in the mineral processing industry for many years, its application in coal cleaning has just begun. The technology is being developed especially to produce premium quality fuel from finely ground coal. The development effort presents a challenge as it involves design of industrial column flotation units and integrated flotation systems to yield clean coal with targeted high quality and nearly complete heating value recovery. Even though performance requirements for the column flotation systems addressed in this report are less stringent, scale-up to the required commercial sizes has to be approached with caution, as penalties for shortcomings, either in clean coal quality of quantity, could be severe.

The record of selective agglomeration and similar oil-based agglomeration processes has been spotty. In addition to the high cost of the fuel oil, the marketability of clean coal laced with fuel oil has been an impediment for wide acceptance of the process. Among other things, fuel oil in coal tends to adversely affect the life of rubber belt conveyors commonly used in coal handling systems. Objectionable smell from oil has also been a problem for such coals. These issues have to be addressed and resolved before plants can be designed and built.

Technical Risks in Thermal Drying

Several processes for thermal drying fine material that are based on proven technology are available. However, fire and explosion hazards presented by fine coal drying systems, combined with requirements to meet environmental regulations governing gaseous emissions, make construction and operation of drying plants complicated and expensive.

Technical Risks in Briquetting

For each powder material to be compacted or briquetted, the most appropriate process conditions (which include operating temperature and pressure, type and quantity of binder, and post-briquetting treatment needs such as curing) are best determined by testing. Test data in this regard for the fine coal products from the Ayrshire, Lady Dunn and Wabash Plants were not available at the time so the Bechtel study discussed a generic briquetting system to convert dried clean coal from the column flotation and selective agglomeration circuits into lumps. In view of the enhanced marketability of the product after reconstitution, compacting or briquetting testing should be included in the product characterization test program.

Benefits of the Near-Term Applications

Recovery of high-quality clean coal from preparation plant streams that are now pumped or hauled to waste disposal sites will benefit the coal industry. The streams pose a disposal problem to plant operators because the fine coal in them cannot be *efficiently* separated from the accompanying ash and sulfur minerals using conventional technology. Near-term application of advanced column flotation and selective agglomeration technologies to process these streams will allow preparation plant operators to recover and sell this coal without incurring additional expenses for mining or crushing. Such applications will also reduce waste disposal costs. Due to the fine particle size of the solids in the streams being processed, the ash minerals should be well liberated. As a result, and as seen from the laboratory testing data, the quality of the clean coal will be better than the existing production from the preparation plant. The benefits, in summary, are (a) a significant increase in the quantity and quality of clean coal produced and in the revenue for the preparation plant at a nominal increase in costs, (b) reduced waste, (c) improved environment due to the reduced use of waste disposal facilities, and (d) better utilization of coal resources in this country.

Viability of Near-Term Applications

The *economic and technical viability of near-term applications* of these advanced technologies depends to a large extent on the specific site and the relationship of that site to the marketplace. As indicated above, the estimated processing costs for the clean coal on a dry coal basis range from a low of $5.63/st to a high of $36.06/st depending on the cleaning technology used, the additional drying and briquetting operations performed on the clean coal, and the specific preparation plant site. Costs for the column flotation options were significantly lower than for the selective agglomeration options.

In the East and Midwest, coal similar in quality to the column flotation product sold for $25 to $35/st in 1993. Cyprus Amax Coal Company was aware of specific instances where mine operators paid in excess of $35/st for high-quality coal for use in blending. The study indicated that there was a large margin between the estimated cost of recovering fine coal and its market price, even if the coal had to be dried and briquetted. The available margin amply justified further development of the technologies for near-term applications, particularly for column flotation, followed by drying and reconstitution of the fine coal into lumps.

Result of Economic and Technical Assessment

In view of the encouraging economic and technical assessment of the column flotation near-term applications, the project team, and especially Cyprus Amax Coal Company, agreed to recommend larger-scale column flotation testing at the Lady Dunn Preparation Plant. The major purposes of the larger-scale testing would be to confirm the cleaning efficiencies and equipment capacities indicated by the laboratory studies and also to provide product samples for evaluation of their dewatering and handling properties and their marketability.

COLUMN FLOTATION TESTING AT LADY DUNN PREPARATION PLANT

In response to the favorable assessment of column flotation by the project team, testing of a 30-inch diameter Microcel^{TM} column began at the Lady Dunn preparation plant in June, 1995.

Objectives of Plant Testing

The objectives of the plant testing of the 30-inch column were several:

- Confirm that advanced flotation processes can be applied to this operating plant.
- Compare the performance of the flotation column to the existing conventional cells on current minus 100-mesh flotation feed.
- Determine the optimum particle size of feed for a column at this plant, i.e., emphasis on coarse coal recovery.
- Further the understanding of the relationship of bubble size and air volume to the recovery of coarser size fractions in coal slurry.

The Lady Dunn plant provided an excellent test site for proving advanced column flotation. The flotation feed typically contained around 40 percent ash and had a high percentage of minus 325 mesh coal and clay in the slurry. Also, the plant had existing mechanical flotation cells so the results could be directly compared to conventional technology.

Test Plan

Meeting the stated objectives required in-plant testing with a column of sufficient size to provide reasonable scale-up information and the utilization of equipment similar to that used in industry. The major results to be evaluated were the percentage recovery of the coal in the various size fractions and the ash content of the various products. The critical scale-up parameters required to provide optimum recovery at a reasonable product ash were investigated. Parameters such as feed rate, aeration rate, frother and collector dosage were varied to determine their effects on the recovery of the various particle sizes of coal.

Selection of Column Size

Scale-up of the Microcel^{TM} column has proven to be successful, even from laboratory size units. Normal in-plant testing could possibly have involved an 8- or 12-inch diameter column, which are usually preferred due to the simplicity of their installation. There was concern, however, that a small-diameter column would not properly simulate a large column in coarse coal recovery. The is a concern due to the very short travel distance of the froth. The short distance may not allow coarse coal particles to drop back in the froth zone in equal proportions to that in a larger-diameter column. To provide a reasonable froth travel distance and to allow for more drop-back in the froth zone, the largest Microcel™ test column available was chosen. There also was a concern that the feed pumps, pipes and valves associated with a smaller column may have plugging problems due to the misplaced coarse particles found in operating plant streams. To accommodate these concerns a 30-inch diameter column was loaned from the Virginia Tech pilot plant. The 30-inch column had been constructed and tested under an earlier DOE project [15].

To develop preliminary feed and control parameter information for the 30-inch column, a drum of flotation feed was collected from the existing plant and tested in a 2-inch diameter laboratory column at Virginia Tech. Scale-up predictions were made from this preliminary test data, and a flotation rate was developed. The scale-up indicated that the total height for the 30-inch column would not need to be any more than 21 feet, which suited the height limitations within the Lady Dunn plant.

The Lady Dunn Plant

At the time of Task 3 testing, the Lady Dunn Plant flowsheet was in transition. Prior to an expansion two years earlier, the plant consisted of heavy media vessels for coarse coal (+1/4 inch), Deister tables for 1/4-inch x 100-mesh coal, and conventional mechanical-cell flotation on the minus 100-mesh material. Around 1993, a heavy-media cyclone (HMC) circuit was added to clean the Deister table feed. Because of increasing demands on the plant for increasing production, however, the tables remained in service to supplement the HMC circuit, allowing more production through the plant. The clean fine coal from the HMC traveled across a large sieve. The sieve underflow was considered to be minus 60 mesh and also sent to flotation. Thus, two flotation feed streams were available for testing. One was a raw minus 100-mesh cyclone overflow and the other was a minus 60 mesh screen underflow containing a 60 x 100-mesh fraction that had been cleaned in the HMC circuit.

Column Feed Streams

Four separate feed slurries were examined before a final slurry were selected as the feed for parametric testing. The four streams were (1) a fine coal stream of minus 100-mesh (-0.15 mm) cyclone overflow, (2) a coarser combined stream of cyclone overflow and partially cleaned screen undersize, (3) a similar steam containing an increased amount of the screen undersize, and (4) a totally raw coal screen undersize stream containing some material that was too coarse for flotation.

Raw coal from the classifying cyclone overflow was the first material tested in the 30-inch column. A thief sample valve was installed in the existing flotation cell distribution box. This valve was adjusted to provide sufficient flow to the column feed sump on the floor below. The feed sump was allowed to have a slight overflow to ensure a constant flow to the column. The results from testing this material were labeled as the 100 series.

While the results of testing the 100 mesh x 0 material were excellent (see test series 101-110 in Tables A-7, A-8 and A-9, Appendix A), testing on a coarser feed was desired by all parties since the intent was to prove column flotation on a broader basis. A valve and collection box were mounted on the side of the sieve underflow pipe which was part of the feed to the flotation cells. This coarse material was blended with the classifying cyclone overflow to simulate the raw coal size consist for a minus 0.25-mm (60-mesh) flotation feed. Several tests were performed on this coarser feed and were labeled as the 200 series (Tables A-10, A-11 and A-12, Appendix A). Screen analyses on the products indicated that there was insufficient coarse material in the blend so the coarse feed valve box was modified to accept nearly all of the material in screen undersize pipe. The flow of this combined column feed proved to be unstable and of insufficient volume for the parametric testing. The two tests performed on the latter feed were labeled as the 300 series (Tables A-13, A-14 and A-15, Appendix A).

The plant had recently installed a test spiral separator, the feed for which was taken from the underflow of a temporary fixed sieve receiving raw Deister table feed (1/4 inch x 0). After completion of the spiral testing, the fixed sieve was changed to one with a smaller opening (1 mm) and the underflow was fed to the column feed sump. This provided a true raw-coal feed containing natural minus 1-mm fines. Since the new column feed was coarser than necessary, the plus 0.5-mm fraction was screened from all of the test samples and accounted for separately. Testing of this raw feed was labeled as the 400 series (Tables A-16, A-17 and A-18, Appendix A).

30-Inch Column Circuit Description and Operation

Although equivalent to a fully functional commercial unit, the 30-inch test column was considered a pilot-scale column. The major difference was the limited capacity of the test unit due to its 30-inch diameter compared to the 3-meter or more diameter of most commercial units. In most cases, the test column has a capacity of 0.5 to 1 ton per hour (tph) of clean coal.

A general layout of the column testing circuit is shown in Figure 25. The column was fed by an 80-gallon feed sump to provide a consistent volume of feed. Diesel fuel was added as a collector into the stream feeding the feed sump. The plant provided a feed pump with a remotely variable speed controller which was adjusted from the control area (near the top of the column) to maintain a given volumetric flow of slurry. The pump and sump were located 2 floors below and over 50 feet horizontally from the column feed area. The column feed piping discharged into a small head box just prior

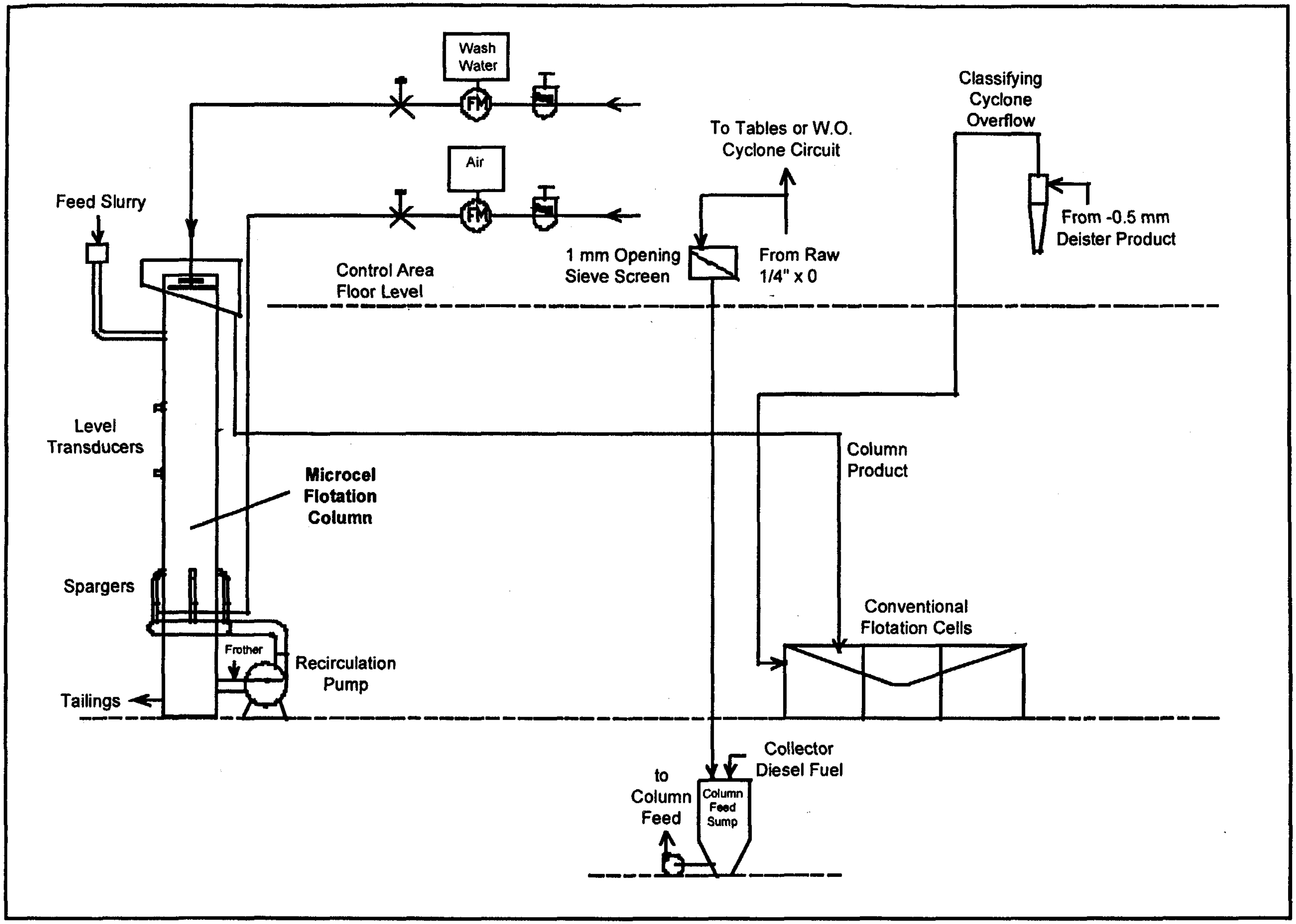

Figure 25. Column Test Circuit Arrangement

to entering the column. By moving a flexible pipe, a full-stream sample cut could be taken and, by noting the time required to fill a fixed volume container, a positively measured flow measurement could also be taken.

The tailings slurry recirculation pump was located on a lower floor at the bottom of the column. By recirculating the slurry through the spargers along with the addition of air and frother, small microbubbles were produced (see schematic in Figure 26). The frother was injected into the suction line of this pump and the air was injected just prior to the spargers. An outlet control valve was also located in this area of the column for discharging tailing slurry through a section of hose. The hose was maneuvered as needed to provide a full-stream cut of the discharge for a fine refuse sample.

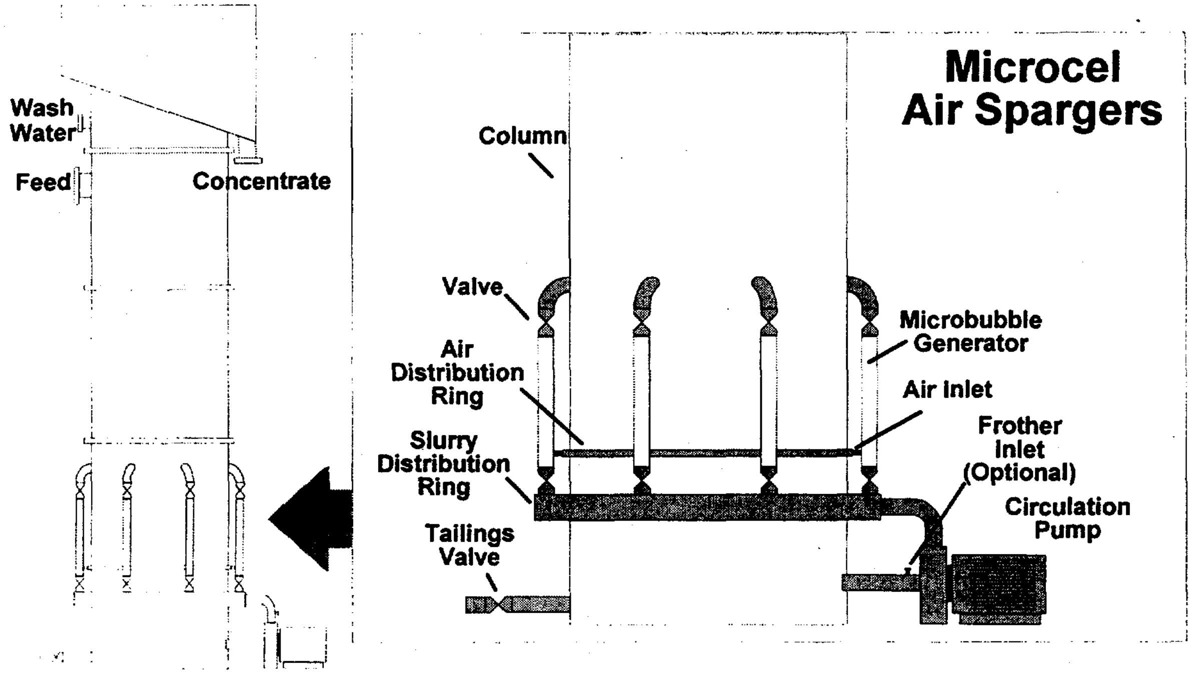

Figure 26. Microcel™ Flotation Column Schematic

The froth from the column launder flowed through a 6-inch diameter pipe to the existing flotation cell product launders. A minimal height difference between the column and existing cells provided little slope for the froth concentrate pipe. This lack of slope caused the clean coal launder to back-up frequently and necessitated the addition of launder water to move the froth through the pipe. For this reason many of the froth percent solids concentration values were somewhat lower than the actual values since the samples were taken at the pipe discharge.

Air, water, and pulp level were controlled from the control area at the top of the column. An orifice plate flowmeter and differential pressure transmitter with digital readout were used to measure air flow to the spargers. The air flow system was equipped with a pressure regulator to provide a constant pressure to the flowmeter. This allowed accurate flow measurements and recording on a standard temperature and pressure basis. Wash water was measured with a paddlewheel flowmeter and displayed electronically. A pressure regulator was provided for the wash water, but low water pressure in the plant required the installation of a small in-line booster pump. Manual gate valves were used to adjust the air and wash water flows.

Pulp level in the column was maintained with a PID loop controller which received a signal from an electronic level transmitter on the column and sent a proportional signal to the tailings discharge valve. The signal from a similar transmitter placed at a lower level was also displayed at the control area allowing an air fraction (fraction of air by volume in a given section of pulp) to be calculated from the combination of the two level signals. Air fraction was calculated as:

$$\text{Air Fraction} = 1 - [((\text{lower level}) - (\text{upper level})) / (\text{fixed distance})]$$

where the lower and upper levels were in vertical inches of slurry and the fixed distance between level transmitters was measured by the transmitters with slurry, but no air, in the column [16].

A small sight glass near the top of the column provided a means to view the pulp/froth interface area. This was an excellent method for determining column conditions such as turbulence, approximate bubble size, or excessive air flow.

Testing involved waiting 30 minutes after any change in the operating parameters to allow all conditions to stabilize before sampling. Several full-stream cuts were taken for each sample and were collected in 5-gallon containers with sealed lids. The samples were sent to the plant laboratory at the end of testing each day.

Testing Results and Discussion

Information was gathered from preliminary testing and from two series of parametric tests. These results are discussed separately.

Preliminary Flotation Testing

The feed slurry for the preliminary testing was taken from the classifying cyclone overflow. The 2-inch laboratory column testing described earlier had indicated that the 30-inch column would have a capacity of no more than 100 gpm of slurry containing the solids concentration of the overflow.

The initial tests with the 30-inch column in the Lady Dunn Preparation Plant on the classifying cyclone overflow stream were labeled as the 100 series. Results were excellent and compared well with the laboratory tests. Both sets of results are plotted in Figure 27 and one can see that the same ash/recovery curve was produced in the two-inch lab column as in the 30-inch diameter pilot-scale column. Figure 28 shows that the efficiency of the two units is also comparable since the points lie along the same curve. The purpose of the initial testing was to develop a general "ballpark" for the expected operating parameters, but before this testing was fully developed, it was decided to try for a coarser feed as discussed previously.

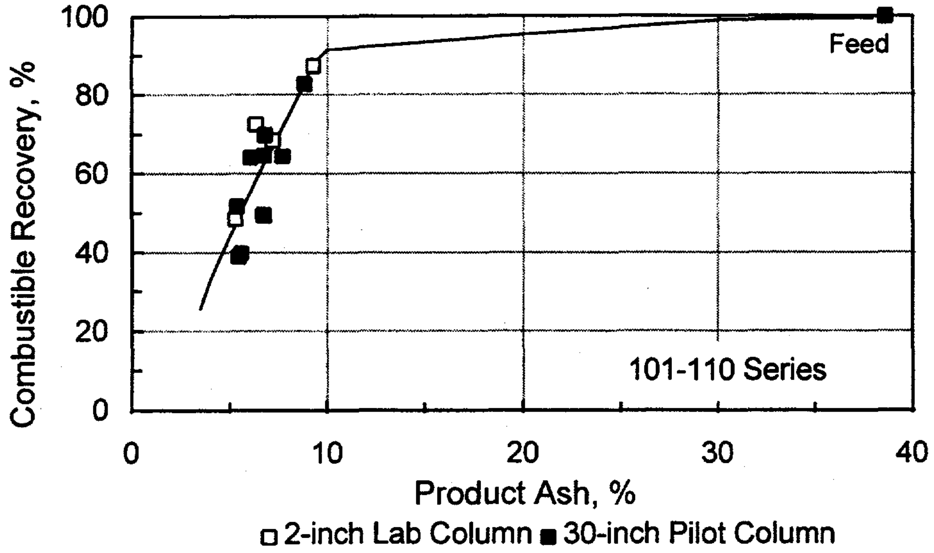

Figure 27. Combustible Recovery vs Ash for 2-inch Laboratory and 30-inch Microcel™ Columns

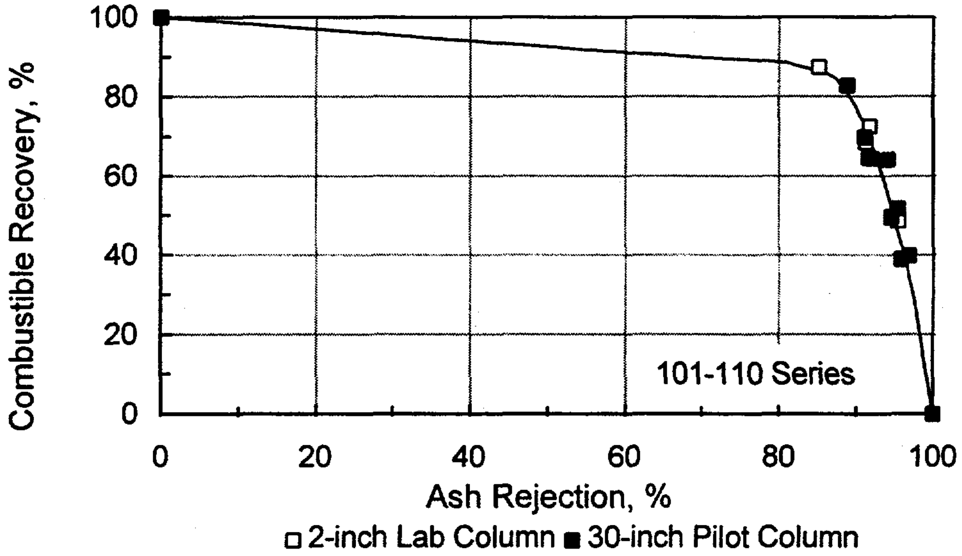

Figure 28. Ash Rejection and Combustible Recovery for 2-inch Laboratory and 30-inch Microcel™ Columns

Testing then began on a coarser feed slurry (200 series). Again this was not fully developed since the stream did not contain as much coarse material as anticipated. Tables A-10, A-11 and A-12 in Appendix A give the results obtained with the limited testing performed on this feed and include a plot of the size-by-size combustibles recovery. Figure 29 shows that the performance was generally well below 10% product ash with a good recovery even though the column had not yet been optimized. The 200 series feed was predominantly classifying cyclone overflow and thus consisted of well liberated fines. An attempt was made to send more coarse material to the column but it was discovered that the available pipe did not carry enough material to feed the pilot column. Results from the two tests performed with this last attempt were labeled 301 and 302 in Appendix A. Testing of combined coarse and fine streams was discontinued when a better stream of raw coal fines became available for feeding the column.

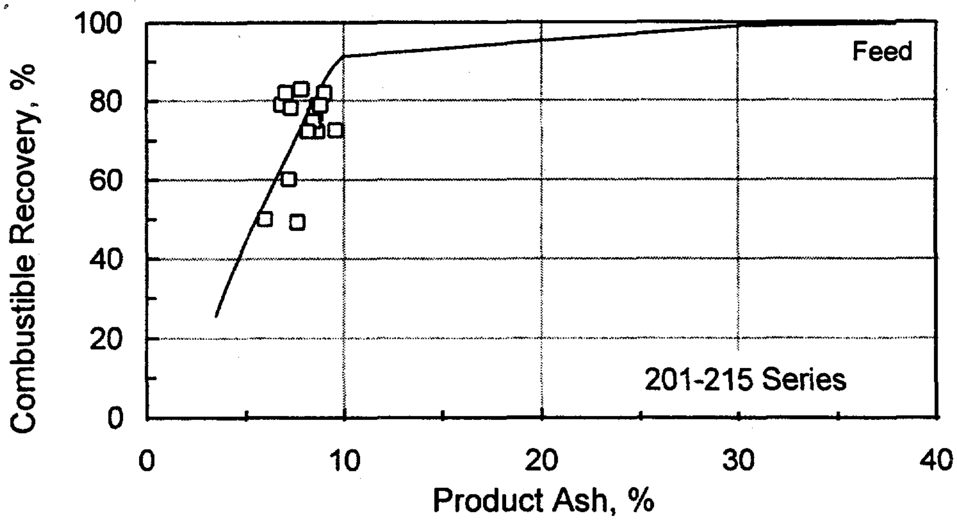

Figure 29. Performance of 30-inch Microcel™ Column for Flotation of Coarsened Cyclone Overflow

At the conclusion of an unrelated test program in the plant, a temporary pipe was installed to carry a 1-mm sieve underflow from a true natural-sized raw coal stream to the column feed sump. Once testing began on the coarse feed there was an urgency to quickly determine the scale-up information for a potential full-scale column installation. Test numbers 401 to 416 are the initial tests to determine the general range of parameters for operation with the coarser coal. Results from these tests are given in Tables A-16, A-17 and A-18, Appendix A and are also considered as a parametric test series.

Parametric Testing

The intent of the parametric testing was to determine the effect of various operating variables on the performance of the flotation column, specifically the recovery of the coarser size fractions of the coal. It was very difficult to provide a consistent feed to the test column as required for the parametric testing due to unplanned variations in the operation of the main plant. For example, during the several days required to run the primary designed parametric test series (tests 451 to 465, Tables A-19, A-20 and A-21, Appendix A), there were considerable variations in feed solids to the column. Other problems, such as low wash water pressure, were also experienced. The problems encountered may explain some of the inconsistencies found when evaluating that data set.

The initial set of data for flotation of the raw coarse coal (tests 401 to 416) provided a much more consistent data set than the later flotation (tests 451 to 465). The intent of this initial testing was to vary key operating variables from low to high to determine likely operating points as well as gain scale-up information [17]. After further review it was determined that the variations in control parameters for the initial raw coarse coal testing fit a Box-Behnken experimental test design. The results produced a consistent data set and prediction model that was better than that produced with the main parametric design. For these reasons the results of two parametric test series (first and second parametric tests) are presented and discussed.

Parametric Tests - First Series

The first set of results (tests 401 to 416) provided the most consistent data set. Changes in several of the key operating parameters were performed, as shown in the operating parameter list found in Appendix B, and were meant to cover the range from low to medium to high for several of the key parameters. Even though this series of tests was not a designed parametric set, when the main parameters (i.e. frother dosage, collector dosage, and feed rate solids) were entered into the statistical analysis program as a Box-Behnken experimental design, good correlations were found and several definite trends were seen. The Box-Behnken design provided a measure of the contribution of each parameter to the given response and also allowed the influence of joint interactions between the various test parameters to be estimated.

Although the test parameters covered a wide range of operating conditions, nearly all of the results fit along a single grade-recovery curve for each particle size range (Figure 30). Results move along an existing grade-recovery curve when bubble loading change. Changes in specific characteristics of the coal particles (i.e., degree of liberation and hydrophobicity) result in a different grade-recovery curve. Column conditions affected the location of a result on the grade-recovery curve. Conditions that resulted in a limited carrying capacity provided room on the bubble surfaces for only the most hydrophobic particles and resulted in a low ash but low recovery product. The close fit to a common grade-recovery curve indicated that, for most of the tests, entrainment of non-floatable material in the froth was not a problem. The wash water flow was sufficient to remove the entrained high-ash particles.

Statistical results are found in Appendix B in Tables B-1 to B-9 which also develop the predictive models. The quadratic model fit best in all cases. To better grasp the effect of variables, only three variables were considered at one time. Although several of the parameters were investigated, those with the most significant effect on combustible

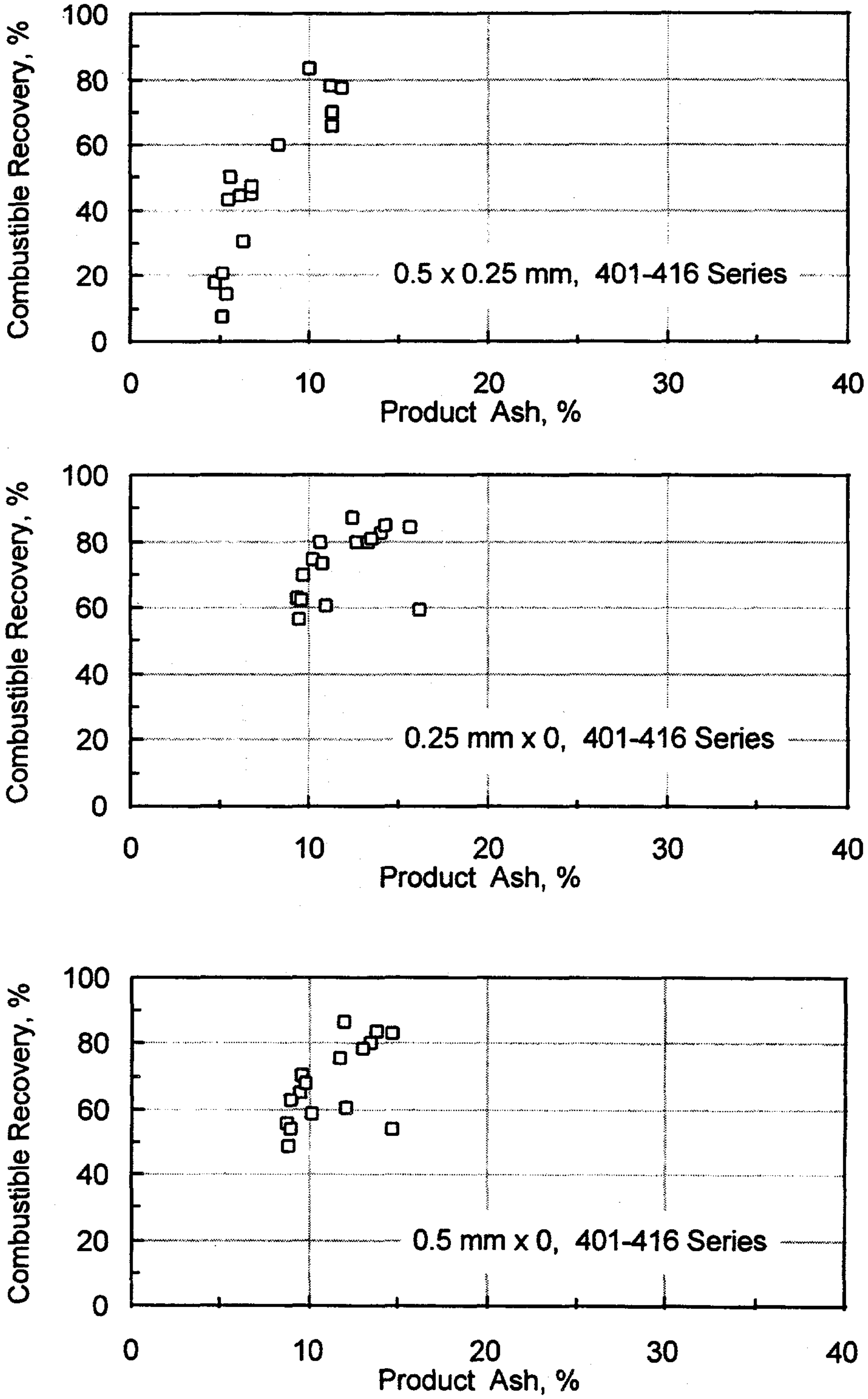

Figure 30. First Series Grade-Recovery Plots of Coarse and Fine Fractions

recovery were feed rate (kg/min), frother dosage (ml/min), and diesel dosage (grams per metric tonne, g/T). The parametric model fits had R-squares of at least 0.94 for the three particle-size classes investigated.

The three particle-size classes were 0.25 mm x 0 (60 mesh x 0), 0.5 x 0.25 mm, and 0.5 mm x 0. These sizes were chosen because one of the main emphases of this test program was to determine the applicability of column flotation to the recovery of coarser coal than commonly practiced. As seen from the size-by-size combustible recoveries plotted in Figure 31, the best recovery during each test was for the 0.150 x 0.045 mm (100 x 325 mesh) size fraction, and the 0.045 mm x 0 recovery was always slightly below that. The hump shaped curves are typical for coal when the recovery from particle above 0.150 mm in size starts to drop off as the particles coarsens. Figure 31 shows that some tests had a much lower recovery for each size class than other tests, while some dropped off mainly at the coarser sizes. The 0.5 x 0.25 mm size class was thus chosen since it was the coarsest size that showed the potential for reasonable combustible recovery from the Stockton seam coal. The combined 0.25 mm x 0 size class was chosen since it was also a relatively coarse size for flotation and includes the effects of the fine coal in the feed. The combination 0.5 mm x 0 particle size range was chosen to show the overall results when floating coarse and fine particles together. The variations in recoveries from 0.5 x 0.25 mm material alone can be misleading unless the total effect, including the effects of fines, is considered. For example, high recovery of the coarser particles of coal can result in an excessive amount of ash in the finer particle-size range of the product. To determine the relationships of the operating parameters that may be causing variations in recovery, the test results and parameters were subjected to statistical analysis using the Design Expert package for the computations.

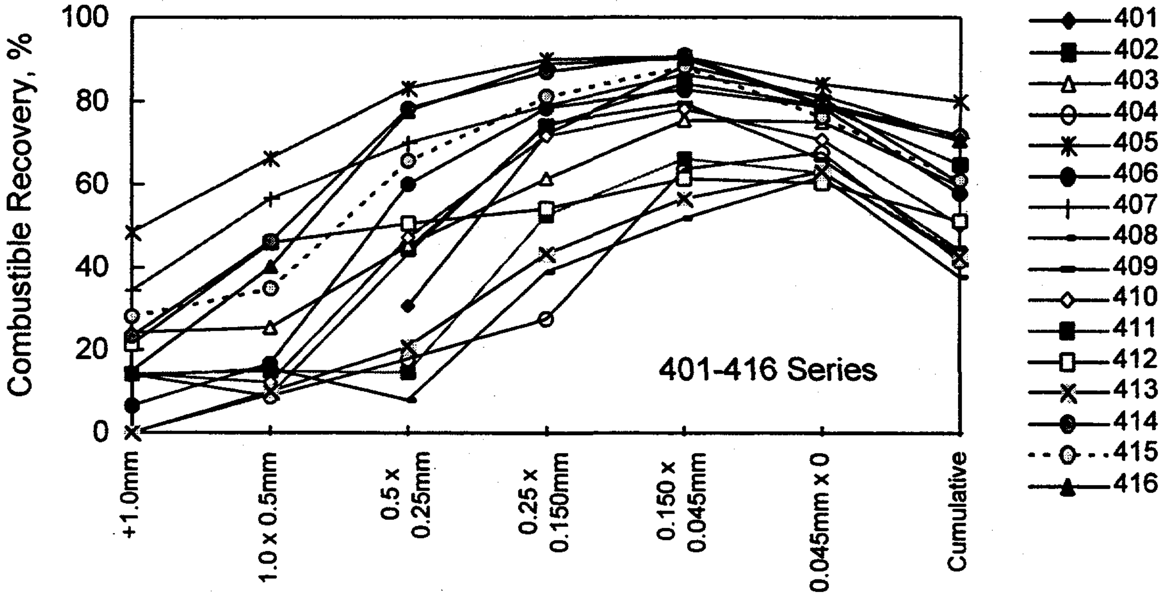

Figure 31. First Series, Combustible Recovery by Particle Size

Looking first at the 0.25 mm x 0 size model as illustrated in a 3D plot (Figure B-1 of Appendix B), one can see that at a low frother dose (8 ml/min), increased feed rate reduced combustible recovery. This was as expected since the larger bubbles which form at a low frother dosage have limited surface areas and quickly become overloaded with coal. A medium frother dose indicated the same performance except that at the higher feed rate, recovery improved over that with the lower frother dose. At a high frother dose (12 ml/min) little change in recovery was noticed with changes in feed rate, indicating sufficient bubble surface area for carrying the range of coal particle sizes available in the feed slurry. Diesel fuel dosage had little effect on the flotation of 0.25 mm x 0 coal except that some improvement in recovery was predicted at higher frother dosages. This was probably because the smaller bubble size and the increased collector dosage together improved the flotation rate constant and provided the extra *bubble* carrying capacity needed to collect middlings particles previously being rejected.

When viewing the 3D plots for the Design Expert predictive model of 0.50 x 0.25 mm size range (Figure B-2 Appendix B), one notices differences from the plot for the smaller particle size range. At the lower frother dose (8 ml/min), combustible recovery was highest at the low feed rate just as for flotation of the smaller particle sizes. Unlike the smaller sizes, however, diesel fuel dosage had a major effect upon recovery of this coarser coal. At low frother and low feed rates, the recovery actually dropped with increased collector addition. This was probably because the excess diesel fuel, above that needed to coat the coal, encumbered the frother resulting in larger bubbles with less surface area. It is well known that fine particles preferentially attach to bubble surfaces and that coarse particles become attached, and remain attached, only if there is sufficient bubble surface available after attachment of the fines. At the medium frother dosage of 10 ml/min and a low diesel dosage, the relationship between feed rate and recovery was similar to that of low frother dosage; that is, increased feed rate meant lower recovery. At the low feed rate, increasing the diesel fuel dosage appeared to lower recovery, probably due to the decreased effectiveness of the frother as described above. At the highest diesel dosages the recovery increased again due to the increased particle hydrophobicity brought about by the large amount of collector available to the coal.

At a high frother dosage (12 ml/min) combustible recovery appeared to have been affected only by the diesel fuel dosage. At the low diesel fuel dosage the recovery of coarse coal was depressed, probably due to "wetting" the surfaces of the coal particles by the excess frother. At higher diesel fuel dosages the coal surfaces are not "wetted" by the frother and maximum recovery was projected by the predictive model.

Figure 31 indicated that 0.50 x 0.25 mm coal can be recovered at some conditions nearly as well as the finer particles of coal. The actual size-by-size recoveries shown in Figure 31 also illustrate the reason that flotation is seldom utilized for clean coal particles above 0.5 mm in size. Even with the best combination of parameters, the combustible recovery began to drop off rapidly as the particles increased above 0.5 mm in size. However, this plot does show that, for most of the tests, coal in the 0.25 x

0.150 mm (60 x 100 mesh) fraction floated as well or better than the coal in any other size fraction.

Parametric Tests - Second Series

Enough was learned about the operating parameters from the preliminary testing to determine the most likely parameter settings for further parametric testing. These settings became the midpoints for a Box-Behnken experimental design. The intent of the second series of parametric testing was to determine the effect of bubble size and air fraction on coarse coal recovery. To do this, air volume and frother dosage were varied. Since any slight variation in feed volume could cause the bubbles to be more or less loaded and therefore affect recovery, feed rate was also intentionally used as a variable. Table 16 gives the settings and testing order for the Box-Behnken design.

Table 16. Test Matrix for the Second Series Parametric Testing

Run Number	Feed Rate	Air	Frother
1	Low	Medium	Low
2	High	High	Medium
3	Medium	Low	High
4	Medium	High	High
5	Medium	High	Low
6	High	Medium	High
7	Medium	Medium	Medium
8	Medium	Medium	Medium
9	Medium	Low	Low
10	High	Low	High
11	Low	Low	Low
12	High	Medium	Low
13	Low	High	Low
14	Low	Medium	Medium
15	Medium	Medium	Medium

Although the earlier testing had shown that the diesel fuel dosage also affected the coarse coal recovery, the intent was to remove it as a variable by holding the diesel dosage relatively constant. This was performed by feeding a different amount of diesel fuel for each of the three volumetric feed rates of slurry (40, 50, and 60 gpm) in order to provide a constant g/tonne diesel dosage as the flow of slurry varied. The percent solids in the feed slurry was to be held constant at 10 percent, but due to variations in plant operation, screen wear on the feed system, and raw coal pumping surges (all unique to this test series) the actual percent solids in the column feed varied considerably. The variation, from 7 to 14 percent solids, had a major impact on the diesel fuel dosage as well. Although the volumetric dosage of diesel fuel was held constant for a given feed flow, the grams per tonne of feed dosage varied with the percent solids changes. Since the diesel fuel tended to coat the fine coal particles first with the remainder then available for the coarser particles, any variation in the amount of fine coal caused the amount of diesel fuel available for the coarse particles to vary considerably. Since coarse coal recovery was sensitive to the diesel fuel dosage, the inconsistencies in coarse coal recovery may have been due to this unintended variation in the ratio of diesel fuel to solids.

The same three major size classes were considered for the second parametric test series as for the first series, that is, 0.25 mm x 0 (60 mesh x 0), 0.5 x 0.25 mm, and 0.5 mm x 0. Test results were entered into the Design Expert statistical computer program. The initial variables entered into the program were the design parameters: air rate, frother, and feed flow. When the program's predictive quadratic model was used to develop the 3D response plots for the 0.25 mm x 0 fraction, variations in feed, air, and frother (within the test ranges) were found to have very little effect on the percentage recovery fine coal (Figure B-4 in Appendix B). For all three frother dosages, the lowest recovery was at the maximum feed flow and air rate. Under these conditions the column would be most turbulent, which may explain the poorer recovery.

When reviewing the 3D predictive plots for the coarser coal (0.50 x 0.25 mm, Figure B-5 Appendix B), the results were more erratic. At a low frother dosage the model predicted a higher recovery at the higher feed rate. This was contrary to normal flotation results since higher feed rates tend to overload the froth, causing lost recovery. The medium frother dosage showed a similar result although not as pronounced. It was obvious that either these results were unique or that something else was happening that would account for the deviation from predictions based on prior experience. At a low feed rate and high air flow, there was a high recovery of coal as one would typically expect At the high frother dosage, the response plot also looked typical with a much higher recovery of the 0.50 x 0.25 mm coal at the low feed-rate, high air corner. This was expected since even though coarse coal particles attach easily to a bubble, many hydrodynamic situations can also arise which detach these same particles. On the other hand, fine coal particles are difficult to detach once they have become attached to bubbles.

The predicted results for the combined 0.5 mm x 0 particle size range are shown in Figure B-6 of Appendix B. These essentially take the shape of the finer size (0.25 mm x 0) plots since the majority of the coal is in that particle size range.

The tight grouping of the test points for the 0.25 mm x 0 material in Figure 32 also show that there was little variation in recovery for the finer material. However, Figure 32 also shows considerable movement up and down the grade-recovery curve for the 0.5 x 0.25 mm material. The lower section of the figure also illustrates the heavy participation of 0.25 mm x 0 material in the overall flotation results for the combined 0.5 mm x 0 fraction. Figure 33 presents additional recovery versus particle size data for tests 451 to 465.

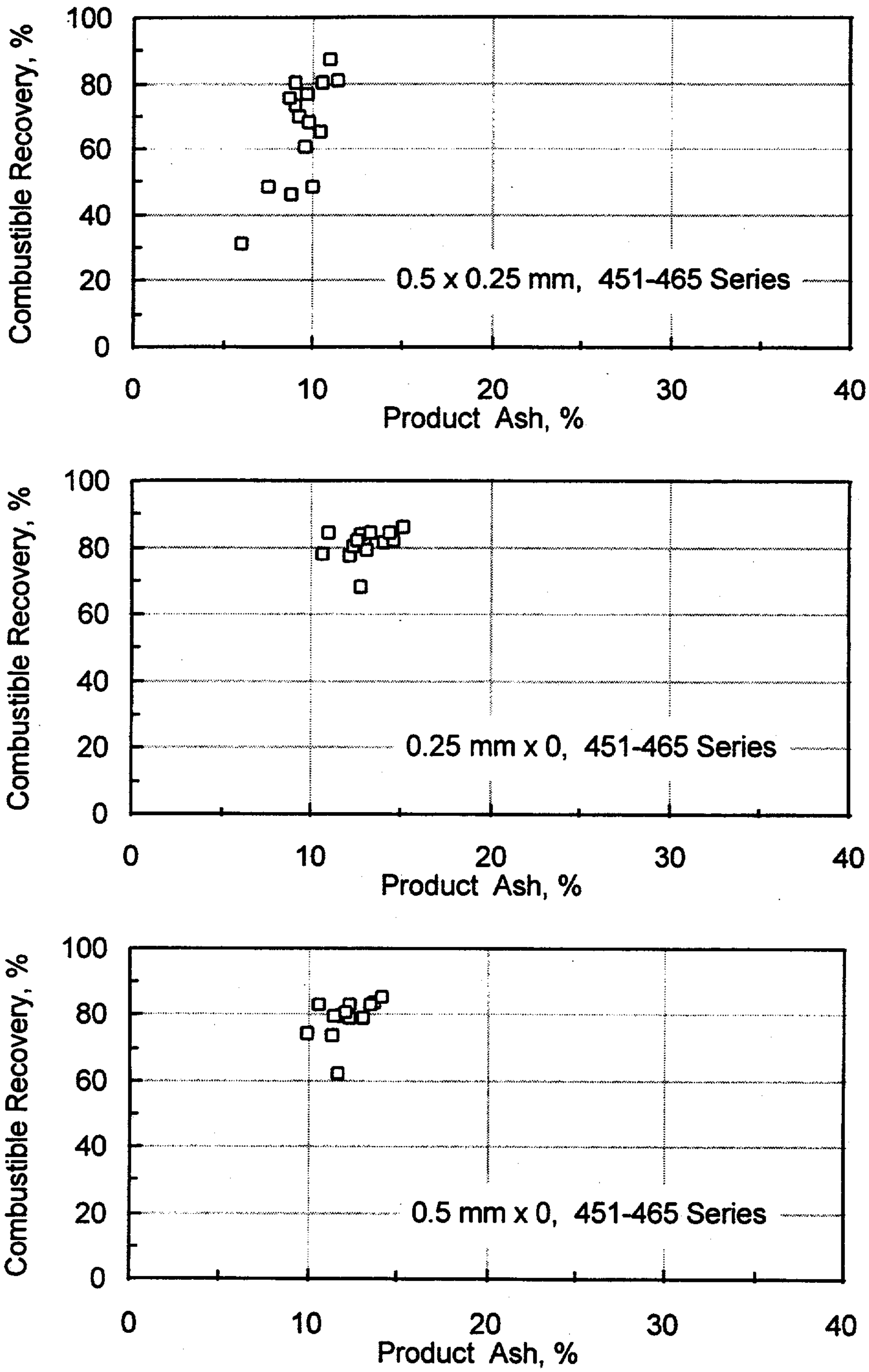

Figure 32. Second Series Grade-Recovery Plots of Coarse and Fine Fractions

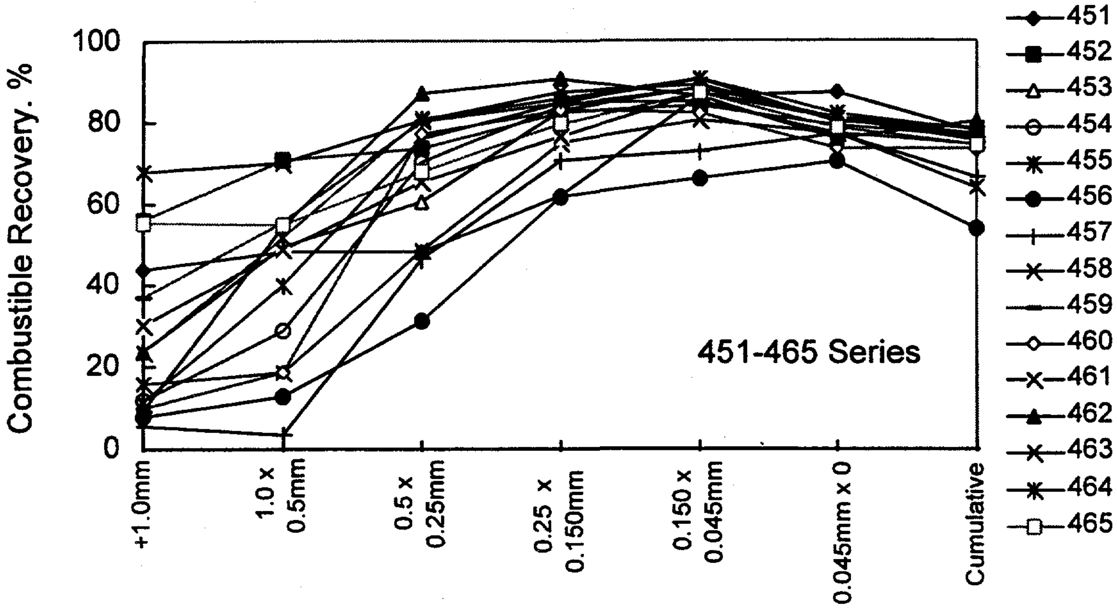

Figure 33. Second Series, Combustible Recovery by Particle Size

Second Series Revisited

After extensive review and cross plotting of the variables and other operating parameters, the question of the inconsistent results from tests 451-465 was resolved. The major problem stemmed from the uncontrollable variation in the percent solids of the feed slurry. Figure 34 is a plot of the effect that the diesel oil dosage (on a gram per tonne basis, g/T) had on the air fraction. It indicated that above a threshold value of diesel fuel (around 1200 g/T for this system), the air fraction dropped rapidly. A decrease in the air fraction from the 10 to 13 percent range down to below 4 percent indicated formation of much larger size air bubbles resulting in less bubble surface area for attachment of coarse coal. Since the fine coal was more strongly attached to the bubble surfaces than was the coarse coal, the coarser particles were the first to be lost when particle loading on the bubbles became high. The larger bubbles may also have caused increased turbulence also resulting in detachment of coarse particles. Feed solids versus diesel fuel dosage has been plotted on the right axis of Figure 34. Since the intent was to hold a constant diesel fuel dosage on the assumption of a constant percent feed solids, it is no surprise that there was an unwanted correlation between feed solids and diesel dosage during the testing.

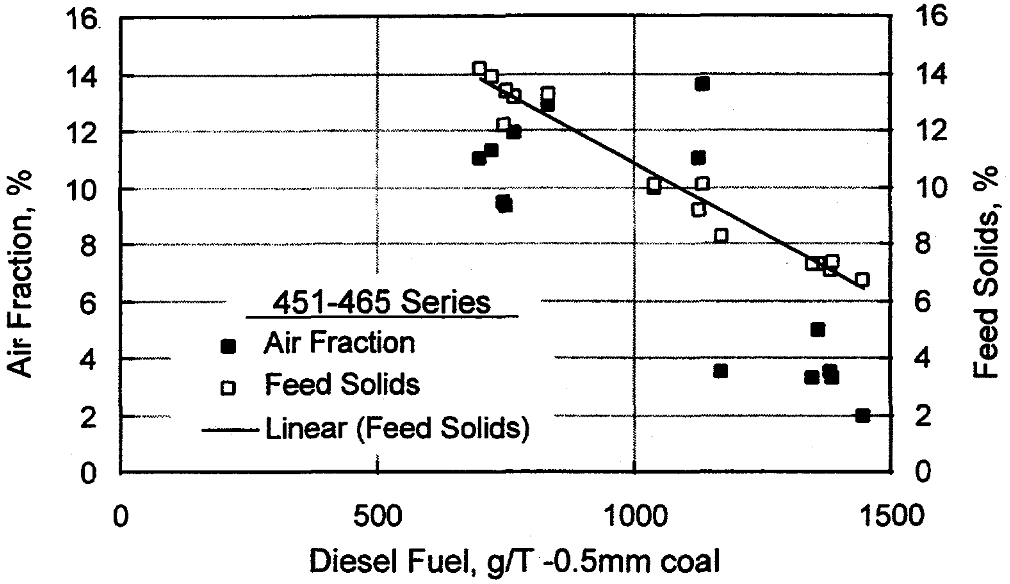

Figure 34. Effect of Diesel Fuel Dosage on Air Fraction

The statistical analysis was re-evaluated using diesel fuel dosage, frother dosage, and feed rate as variables. In the previous analysis of this set of data, air flow was found to have a very small effect and could be dropped to allow room for the diesel fuel dosage to be evaluated in the statistical model. (With only 15 test points, 3 variables are the most that can be evaluated using the Box-Behnken design). The 3D response plots (Figures B-7, B-8 and B-9) for this evaluation are found in Appendix B. From the 0.25 mm x 0 plots of the predicted coal recovery, one can see that the changes in recovery due to differences in frother dosage were small. The best performance was at the medium frother dosage while the lowest recovery was found at the extremes of high diesel fuel dosage, high feed rate, and low frother dosage. At the low feed rate, the diesel fuel dosage accounted for a slight recovery increase at all but the lowest frother dosage. However, the differences in the observed recovery of coal between the tests on this fine particle size fraction were small so predictions of the recovery response are not very reliable within the range of the operating parameters tested.

Combustible recovery from the 0.50 x 0.25 mm fraction had a much broader range of response in the prediction model. A change in recovery at low diesel fuel dosages was the most significant variation observed. Recovery dropped considerably at all the feed rates with increasing frother dosage. The decrease in recovery at the high frother dosage was possibly due to the "wetting" the coarse coal by the excess frother which reduced their hydrophobicity enough to allow the particles to drop out of the froth back into the pulp. At the higher frother dosages increasing the diesel fuel dosage improved the recovery by overcoming the effect of the excess frother. An unexpected response was the increase in recovery with increasing feed rate and low diesel dosage. An increased feed rate normally overloads bubble surfaces and decreases recovery, but in this case the increased feed rate may have diluted the frother and reduced its negative effect as long as sufficient bubble surface was available.

The predicted flotation response of the 0.50 mm x 0 composite was obviously a combination of the response of the two previous particle size ranges, but it does indicate very well the detrimental effect of excess frother on coarse coal recovery.

All of the test work presented here showed that coarse coal can be floated successfully when attention is paid to control parameters such as air, frother, diesel, and feed rate. Laboratory test work on coarse-particle flotation is always difficult due to particle settling, differences in samples, etc. Producing a coarse slip stream in an operating plant is also difficult, as discussed previously. Replication of the major parametric test at the Lady Dunn Plant was not possible for this project due to the onset of construction for a major plant upgrade. Therefore, the 30-inch column was removed from the plant shortly after completion of the last test series.

Conclusions from Pilot Testing

Coarse coal flotation is alive and well. The test work presented here illustrates very well the potential for coarse coal flotation in a properly operated flotation column. Figure 32 illustrated nicely that particle up to 0.25 mm in size can be floated consistently in a column. It was also shown that coarse coal up to 0.5 mm in size also floats well in a column, but coal recovery drops off rapidly above that size. Since it is difficult to separate fine particles accurately by size, with little misplaced material, making a nominal 0.25-mm cut and sending the minus 0.25-mm fraction to a flotation column should work well in coal processing plants. As long as the misplaced coarse material in the column feed is finer than 0.50 mm, the column can provide good recovery of clean coal with a low ash content.

A 0.25-mm nominal cut is different from traditional coal processing plant applications where the particle-size cut is more often made at a nominal 0.150 mm (100 mesh). The difficulty in making such a fine cut results in a considerable amount of misplaced high-ash fine material in the coarser fraction. All gravity devices for cleaning plus 0.150-mm streams allow most of this misplaced fine material to report to the clean coal launder without cleaning (i.e., as high-ash raw coal). Thus, the incomplete removal of fines from coal streams results in a higher ash clean coal product. On the other hand, a flotation column utilizing wash water can remove high-ash slimes as well as recover the 0.25-mm coal better than other cleaning devices for fine coal. By taking more of the fines that would otherwise be routed to the fine gravity cleaning circuit, column flotation becomes an attractive option for a preparation plant operator.

All indications are that a flotation column will perform much better at the Lady Dunn Plant where the original mechanical flotation cells produced an average of 14 to 16 percent ash clean coal at a 20 percent combustible recovery. Results from testing the 30-inch diameter column indicate that clean coal containing 10 to 11 percent ash can be obtained from the 0.25-mm x 0 fines at a combustibles recovery of 75 percent. Similar results have been observed at other column flotation installation where the feed slurry has finer particle size distribution than here [18].

The success of this test work was made tangible by the installation of three Microcel™ flotation columns, each four meters in diameter, in the Lady Dunn Preparation Plant. These are the largest known flotation columns for processing coal. Cyprus Amax Coal Company installed the columns in the plant on the basis of the good results of the test work described in this report. The columns have been successfully cleaning 0.25-mm x 0 coal and producing results that fit on the ash/recovery curves presented here.

ENGINEERING DEVELOPMENT OF AUXILIARY OPERATIONS

The froth overflowing the test column was a slurry containing 10 to 20 percent coal. The dewatering characteristics of this slurry were investigated during Task 3 as were the briquetting properties of the dewatered cake.

Dewatering

Consideration was given to methods for dewatering the froth from Microcel™ flotation of the Lady Dunn fines. Centrifuging and vacuum filtration were evaluated for this application. In this regard, twelve drums of froth slurry were collected from the 30-inch Microcel™ system and shipped to DOE/FETC, Pittsburgh for centrifuge testing by the Coal Preparation Research Division (CPRD). The column was receiving combined cyclone overflow and minus 48-mesh screen undersize at the time the clean coal froth was being collected. Additional drums of the froth products were shipped to Amax R&D for testing there. The vacuum filtration tests were done on-site by Westech Engineering, Inc. representatives using fresh slurries. Westech also performed follow-up filtration tests later on at their facility in Salt Lake City.

Centrifuge Dewatering

CPRD conducted the centrifuge dewatering tests at the Federal Energy Technology Center, Pittsburgh using their patented GranuFlow process [19]. Between 2 and 8 percent of an asphalt emulsion from Venezuela called Orimulsion was added to the centrifuge feed during the GranuFlow process in order to improve the properties of the dewatered product. The properties most effected by the Orimulsion are the moisture retention and handleability (stickiness and potential dustiness) of the cake. Baseline tests were performed without the additive as well.

Two types of continuous-feed centrifuges available at FETC were used for the dewatering tests. The first was a laboratory 6-inch diameter, 576 g-force screen-bowl, and the second was a 14-inch diameter, high-speed (1789 g-force) solid-bowl. The g-force in the 6-inch screen-bowl was similar to g-forces in the screen-bowl centrifuges commonly installed to dewater fine coal while the g-force in the 14-inch solid-bowl was similar to the g-forces in recent-vintage high-speed solid-bowl decanter centrifuges.

Figure 35 is a plot of the residual moisture in the centrifuge cakes versus the amount of Orimulsion added to the clean coal froth slurry. Without the Orimulsion, the screen-bowl cake contained 39 percent moisture, and the solid-bowl cake contained 35 percent moisture. The difference between the two results indicated the added effectiveness of higher speed centrifuging for reducing cake moisture. Adding 6 to 8 percent Orimulsion decreased the residual moisture to the 35-36 percent range in the case of the screen-bowl tests and to 31 percent in the case of the solid-bowl test.

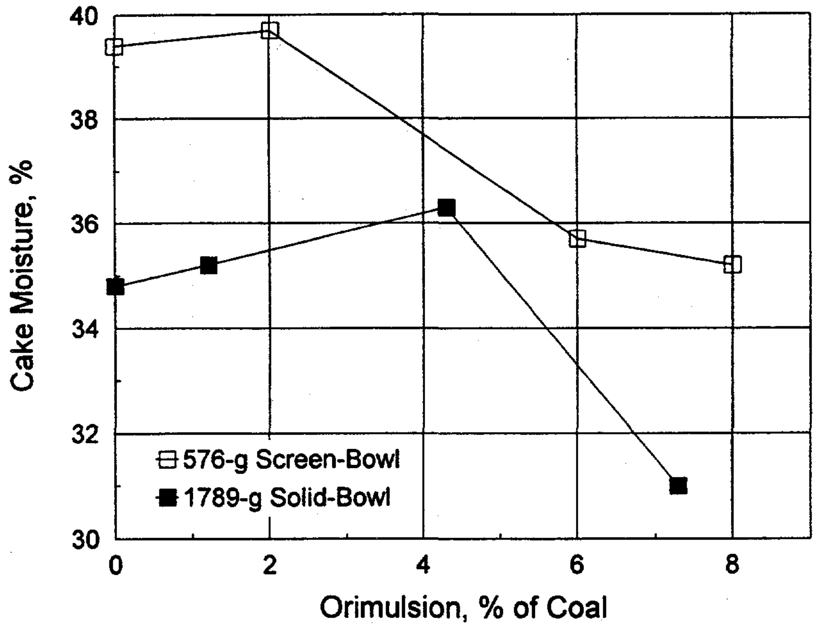

Figure 35. Cake Moisture versus Orimulsion Addition When Centrifuging Lady Dunn Microcel™ Froth Slurry

Further results of the centrifuge testing are presented in Table 17. As seen in the table, GranuFlow processing with Orimulsion had other benefits besides moisture reduction. First, the potential dustiness of the cake upon drying was reduced by the agglomeration of fines with the asphalt. This is shown by the changes in the Dust Index and the Dust Reduction Efficiency entries in the table. These are measurements of the amount of minus 100-µm material released during sieving tests on dried cakes[1].

The agglomeration also reduced the stickiness of wet cakes, and test 16-4 (see Table 17) in the solid-bowl centrifuge produced free-flowing granules. A further benefit of GranuFlow processing was the improved solids recovery during screen-bowl centrifuging, also due to the agglomeration of the fine particles in the slurry. Solids recovery was even better when dewatering with the high-g solid-bowl centrifuge, and the resulting effluent may have been clean enough to be reused without further clarification.

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[1] Dust Reduction Efficiency, %:

$$E = \frac{(I_o - I_i)}{I_o} x100$$

where I_o = Dust Index of feed coal, weight % minus 100 µm by wet screening
and I_i = Dust Index of cake, weight % minus 100 µm in dry cake by Ro-Tapping 5 min

Table 17. GranuFlow Centrifuge Results

Test	Orimulsion wt %	Cake Moist, %	Main Effluent, % solids	Dust Index	Dust Reduction Efficiency wt %	Solids Recovery percent
6-inch Screen-Bowl Centrifuge (g-force = 576):						
17-1	0	39.4	1.13	83	3	89.5
17-2	2	39.7	1.40	34	0	92.0
17-3	6	35.7	0.91	7	92	95.1
17-4	8	35.2	0.73	4	95	96.5
14-inch Solid Bowl Centrifuge (g-force = 1789):						
16-1	0.0	34.8	0.17	73	15	98.6
16-2	1.2	35.2	0.10	66	23	99.2
16-3	4.3	36.3	0.12	13	85	99.0
16-4	7.3	31.0	0.10	7	92	99.2

Vacuum Filter Dewatering

Laboratory vacuum filtration leaf tests were conducted on the froth slurry by Westech Engineering Inc personnel [20]. The objectives of the leaf testing were to project the capacity and performance of top-feed horizontal belt filters and of bottom-feed drum filters. The laboratory evaluation included a test of the benefits of layering spiral concentrate onto a horizontal filter ahead of the froth slurry in order to form a deep bed of natural filter media.

Top-Feed Procedure: These tests were conducted by pouring slurry onto a horizontal filter leaf. The filter test leaf consisted of a round disk with drainage grooves and a cloth support grid on one side and a valved vacuum and filtrate discharge connection on the other side. A filter cloth and a dam high enough to retain the required volume of slurry (typically less than 650 ml) were clamped around the edge of the disk. The effective filtering area of the leaf was about 0.078 sq ft.

Before the start of each test, the test leaf was placed in position on top of a vacuum flask with the drain valve closed, and the desired quantity of slurry placed in an Erlenmeyer flask. Next, the vacuum was turned on and adjusted to the desired level. After that flocculant was mixed with the slurry, and the flask vigorously swirled to put all of the solids into suspension. Then, in quick succession, the slurry was poured onto the test leaf, the valve beneath the leaf opened to apply vacuum, and the timer started.

Each test run consisted of the two operations of cake formation and final drying, with the cake formation time taken as the time required for all of the free slurry to disappear from the surface of the cake. After the final dry time, the vacuum was turned off and the cake discharged. The following observations were recorded for each test run:

- Vacuum level
- Cake formation time
- Final dry time
- Final cake thickness
- Wet and dry cake weights
- Filtrate volume and an evaluation of its clarity
- Quantity of flocculating polymer used
- Volume of air passing through cake during drying period (optional)
- Ease of cake discharge and amount of cake remaining on cloth

Some of the tests involved the application of an initial layer of coarse spiral concentrate followed by a second layer of froth slurry. A special procedure was followed to allow the second layer to form without unduly disturbing the layer of coarse solids. This allowed the initial layer to act as a filter medium for the froth slurry. For a few other tests the spiral concentrate was mixed directly with the froth slurry prior to filtration as well.

<u>Bottom Feed Procedure:</u> These tests were conducted by dipping the filter leaf down into the feed slurry. The equipment was essentially the same as the equipment for the top feed testing except that a hose connected the filter leaf to the vacuum flask and the dam around the leaf was only slightly deeper than the expected cake thickness.

About one gallon of slurry was placed in a bucket and flocculated with a power stirrer for these tests. Mixing continued for about 30 seconds after the polymer addition was completed. When starting these tests, the hose between the test leaf and the vacuum flask was crimped by hand and the vacuum adjusted to the desired level. The leaf was then immersed in the hand- or paddle-agitated slurry. Time was started as soon as the crimp in the hose was released. After the desired cake formation period, the leaf was removed from the slurry and held with the cake uppermost for the final drying. At the end of the desired drying time, the vacuum was shut off, and all of the observations noted for the bottom-feed tests were made for the top-feed tests as well.

<u>Test Variables:</u> Two types of froth slurry were tested:

- Froth from the column when receiving “fine feed” (minus 100 mesh cyclone overflow)

- Froth from the column when receiving “coarse feed” (cyclone overflow plus a small amount of minus 48 mesh coal from another stream).

As a practical matter the particle size distributions of the two froth slurries did not differ very much. A considerable amount of launder water was required while producing the two slurries so they only contained 10 to 12 percent solids. Most of the tests were carried out on the slurries at their as-received solids concentration, but additional tests were conducted later after the slurries had been thickened to 15 to 20 percent solids as if only minimal amounts of launder water had been used in the plant. Unit filtration capacities improved with the higher solids concentration feed slurries.

The use of the coarse spiral concentrate (basically 10x150 mesh) as a filter aid was evaluated for the top-feed filter tests only. The spiral concentrate was available from a separate test program at the Lady Dunn plant. The coarse fraction was added at ratios between 0.37 and 1.71 pounds (dry weight) of spiral concentrate per pound of froth slurry solids. As indicated above, the coarse material was evaluated as an initial layer (similar to a precoat) for the filter and as a bulking agent mixed in with the froth slurry feed. The weight of the spiral concentrate additive (and accompanying moisture) was deducted from the total weight of the cake when projecting filter test performance. It was found that the projected filter performance did not change appreciably when changes were made to the spiral concentrate/froth solids ratio.

The froth slurries and the spiral concentrate both contained a considerable amount of residual clay. The use of a low to medium molecular weight anionic polymer was soon found to be beneficial for flocculating the slurries before filtration and such flocculants were added both to the clean coal froth slurry and to the spiral concentrate during most of the tests.

An intermediate-permeability cloth (POPR-859, 100 cfm/sq ft permeability) worked quite well with the flocculated slurries, and it was used for most of the testing. Sixty and 300 cfm/sq ft cloths were also evaluated. It was necessary to wash the cloth after each test since the cloth blinded after a few cycles. Coarse material from the layered sequence cycles also tended to adhere to the cloth and necessitate a washing step after each cycle. A submerged-blow cleaning procedure was tried but with questionable success.

Cake formation times were selected to bracket formation of 3/8- to 1/2-inch thick cakes, and drying times were selected to bracket practical drying time cycles for commercial horizontal belt and bottom-feed scraper- and belt-discharge drum filters. It should be noted that a 3/8-inch cake is about the minimum thickness cake that will discharge reliably from a filter cloth.

Projections of Filter Performance: A total of 122 laboratory vacuum filtration leaf tests were performed. Westech employed engineering correlations to project filter performance from these data, the principal correlations being form time versus cake thickness or weight and drying time versus the amount of moisture remaining in the cake. Capacities of operating vacuum filters were then calculated from these correlations using practical cycles of cake formation, drying, discharge and cloth washing periods for the individual types of equipment. Because of the cloth washing requirement, the performance projections were limited to top feed horizontal and bottom feed drum belt filters. Table 18 is a summary of the Westech projections when producing 3/8-inch thick cake. Projected capacities were less when producing 1/2-inch thick cake, but cake moistures were unchanged.

Table 18. Projected Filter Performance for Dewatering Lady Dunn Microcel™ Froth Slurry

		Froth Coal Basis Only			
Feed Slurry	Spiral Conc/ Float Coal Ratio	Feed Slurry % Solids	Flocculant lb/ton	Capacity lb/hr/sq ft	Cake Moist, %
		Top Feed Horizontal Belt Filter			
Coarse Column Feed Froth:					
Layered Spiral Conc	0.6	9.8	0.03	50.4	35.5-38.5
Mixed Spiral Conc	0.6	9.8	0.03	48.8	41-43
No Coarse Material		9.8	0.08	53.0	34
No Coarse Material		18.1	0.17	57.6	43
Fine Column Feed Froth:					
Layered Spiral Conc	0.6	11.5	0.07	58.9	36.5-40.5
Mixed Spiral Conc	0.6	11.5	0.08	49.2	42-44
No Coarse Material		11.5	0.10	45.1	39
No Coarse Material		15.0	0.04	80.7	37
No Coarse Material		20.0	0.04	90.8	37
		Bottom Feed Drum Belt Filter			
Coarse Column Feed Froth		9.8	0.08	32.2	34-35
Fine Column Feed Froth		11.5	0.07	42.6	35

There were some ambiguities among the capacity and cake moisture projections which may have been due to the differing amounts of flocculant required for each situation. However, it was clear that filtering coarse spiral concentrate along with the froth slurry, either by layering or by premixing, offered little, if any, advantage with respect to unit capacity or moisture removal. A horizontal-belt-filter cycle appeared to offer a somewhat higher capacity on a lb/hr/sq ft basis than a drum-belt-filter cycle but the moisture contents of the resulting cakes were all about the same, that is, in the 34 to 43 percent range.

Because the filter-cake moistures were little different from the centrifuge-cake moistures, Lady Dunn Plant management decided to continue with their plan to dewater the column flotation froth with a screen-bowl centrifuge after the plant expansion in the same manner as the mechanical-cell froth was being dewatered in their existing plant.

CWF Formulation

Marketing the clean coal from the column flotation as slurry fuel rather than as filter or centrifuge cake was also investigated. Slurry preparation tests were performed on froth slurry from the Microcel™ testing at the Lady Dunn plant. The tests were on the froth slurry alone and on the froth slurry blended with coarser slurry prepared by stage grinding spiral concentrate. In the latter case, the spiral concentrate provide coarse particles for formulation of more highly loaded slurry fuel than possible with the froth slurry alone.

The spiral concentrate contained more ash and slime than anticipated so it was deslimed to provide a lower-ash source of coarse material for fuel preparation. The minus 150 mesh slimes that were rejected contained 44.71 percent ash, and the ash in the desliming concentrate was lowered to 15.96 percent. The deslimed spiral concentrate was next stage-ground to minus 48 mesh (as in a closed-circuit grinding system). The stage-ground product was 20 percent plus 65 mesh and 54 percent plus 150 mesh so it was a good source of coarse particles for blending with the very fine coal naturally in the froth product. Two blends were prepared, one containing 10 percent coarse material and 90 percent fine material and the other containing 40 percent coarse material and 60 percent fine material, both on a dry coal basis. Properties of the two blends are compared to the properties of the froth and the ground spiral concentrate in Table 19.

Table 19. Properties of CWF Slurries

	100% Fine, Microcel™ Froth	10% Coarse 90% Fine Blend	40% Coarse 60% Fine Blend	100% Coarse, Stage-Ground Spiral Concentrate
Ash (dry basis), %	6.86	7.77	10.50	15.96
Nominal Top Size, mesh	100	48	48	48
Minus 100 mesh, %	97.0	93.8	83.3	62.7
Minus 400 mesh, %	74.8	70.1	53.6	22.3
MMD, µm	37	45	74	130

The first of the slurry preparation tests was on filtered Microcel™ froth using a bottle rolling technique with 1 percent A-23 dispersant in the mixture. A pourable slurry containing 60.1 percent coal was prepared in this manner. Its viscosity was 430 cP at 100 s^{-1}. A loading of 61.8 percent coal at 500 cP was projected by extending the trend line to 500 cP as shown in Figure 36. Ten percent dry 48-mesh x 0 ground spiral concentrate was next added to the filter cake slurry to prepare a 10 coarse/90 fine blend. The additional coarse material raised the coal loading to 61.4 percent and the slurry remained pourable. A projected loading of 63.2 percent coal at 500 cP could only be guessed since a small dilution appeared to have increased the viscosity rather than decreasing the viscosity indicating the occurrence of wall-slip during the viscometer measurements [21].

The 40/60 blend slurry was obtained by mixing the 10 percent blend slurry formed above with an additional amount of 48-mesh x 0 ground spiral concentrate. In this case the spiral concentrate was first mixed with 1 percent A-23 and water to form a paste before mixing with the starting slurry. Wall-slip did not appear to occur this time, and a loading of 68.0 percent coal at 500-cP viscosity was projected for the 40/60 blend as shown in Figure 36.

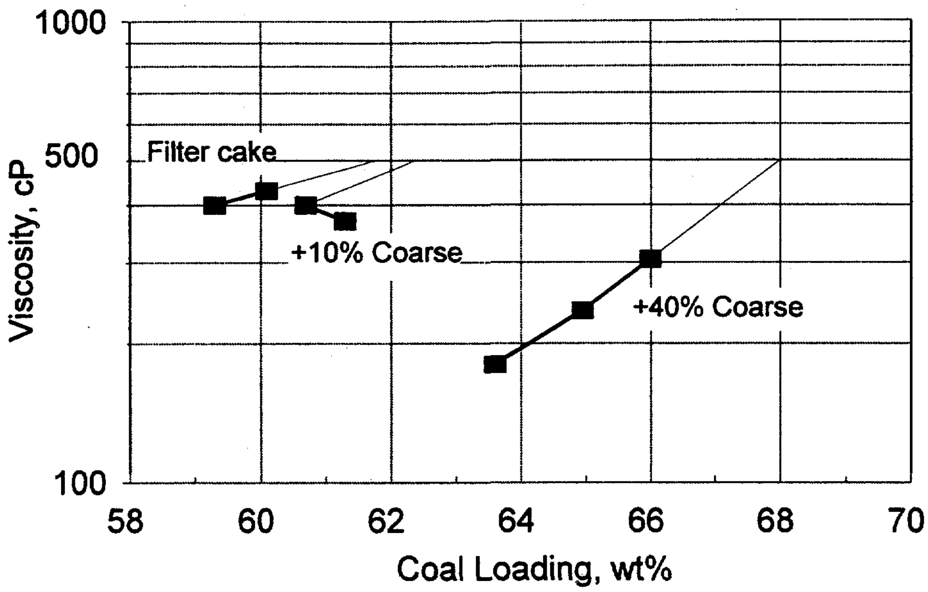

Figure 36. Observed and Projected Loadings of Lady Dunn Slurry Fuels

All of the slurries prepared from the Lady Dunn coal were pseudoplastic, and the blended slurries had very good overnight stability. All in all, it appears that a useful coal slurry fuel containing 62 percent coal can be prepared from the Lady Dunn Microcel™ froth and one containing 68 percent coal can be prepared by blending coarser coal with the froth slurry.

If a niche market can be found in the Charleston area, it may be possible to sell the fine clean coal as a slurry. This would eliminate some need for a dewatering step. However, it appears at present that dewatering the froth with a centrifuge and blending the cake with the normal plant production is the better alternative in terms of cost and marketability.

Briquetting

A portion of the clean coal from the Microcel™ parametric testing was submitted to TraDet Inc. (Triadelphia, WV) for binderless briquetting tests. Good quality specimens of the briquette production were returned by TraDet, who reported that the briquetting was done at near-ambient temperature on minus 16-mesh clean coal flotation product that had been air-dried to between 1.0 and 2.4 percent moisture [22]. The briquettes contained 11.8 percent ash and 34.2 percent volatile matter and had an estimated heating value of 12,900 Btu/lb.

A model B-100A Komarek laboratory roll-press machine was used which has 5.1-inch diameter rolls. Pillow-shape briquettes approximately 1 5/8 inch long by 3/4 inch wide by 1/2 inch thick were produced. The rolls were preheated to equilibrium operating temperature by briquetting waste material for about 10 minutes before switching to the test coal. Feed rates were between 74 and 168 lb/hr. Parametric tests were made at three roll speeds and at hydraulic roll pressures of 1,300, 1,600, 2,000, 2,400 and 2,800 psig. At the measured product temperatures of 128° to 178° F, these pressures deformed the coal particles and fused them together. The tests were repeated on each of four batches of the flotation product that had been dried to differing moisture levels. (The PSD of the dried coal is presented in Appendix Table A-22.) The primary response considered was the average crush strength of 15 randomly selected briquettes produced during each set of test conditions. The densities, moisture reabsorption, degradation, and weathering of the briquettes were evaluated as well.

Average crush strengths between 50 and 200 lbs were seen during the testing, and these strengths correlated well with the amount of energy transferred to the briquettes (between 8 and 29 kWh/ton) as seen in Figure 37. TraDet considered any strength over 100 lbs to be acceptable for briquettes such as these. The hydraulic pressure holding the rolls together, in particular, had a significant impact on the energy transfer and resulting improvement in crushing strength. The effect is shown in Figure 38. The best briquettes were made from feed coal that had been dried the most, that is, to 1.0 percent moisture. The products from all 58 tests had acceptable moisture reabsorption, weathering and briquette degradation properties.

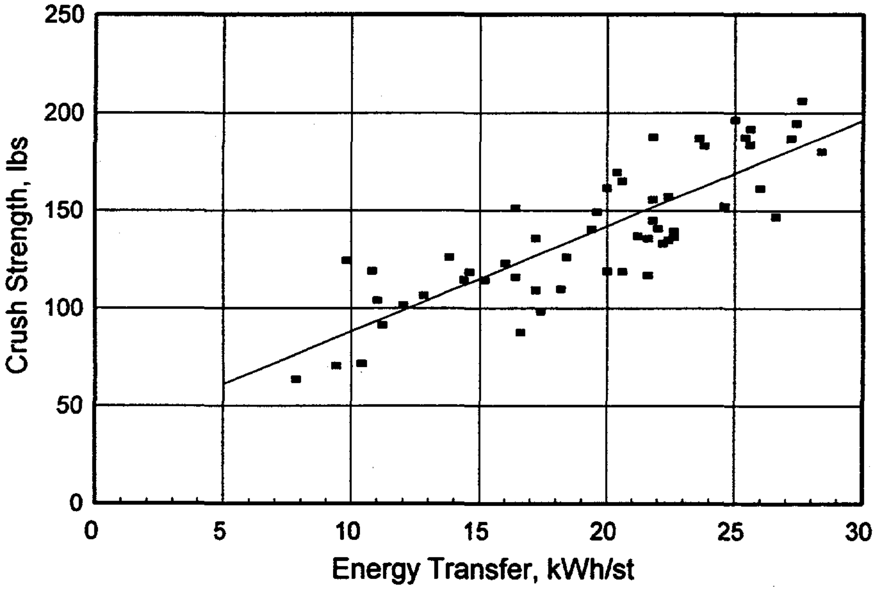

Figure 37. Strength of Briquettes vs Energy Transferred to Briquettes During Compaction

Note: Energy transfer equals energy input to feed screw and roll drive less energy consumed by the evaporation of moisture during compaction.

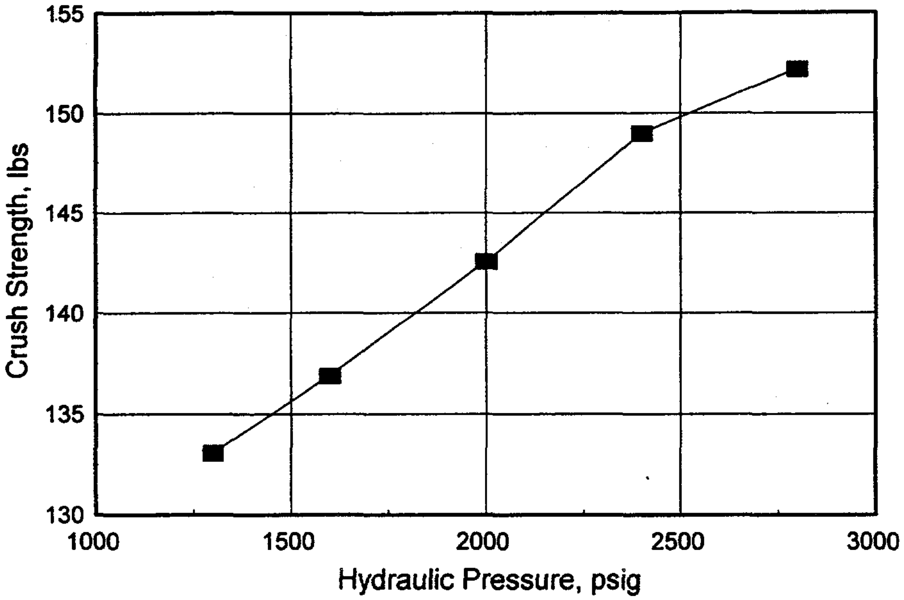

Figure 38. Effect of Pressure on Briquette Strength -- Lady Dunn Flotation Product

Note: Values are averages across all roll speeds and moistures.

TraDet considered the B-100A briquetting results to be favorable indications of the potential for binderless briquetting of the flotation product from the Lady Dunn Preparation Plant. They suggested follow-up optimization testing in a larger, pilot-size machine (such as a Komarek Model DH-300 briquetter) to allow scale-up of briquetting performance to commercial/production units.

CONCLUSIONS AND RECOMMENDATIONS

The conceptual engineering analysis of laboratory column flotation and selective agglomeration test results and the confirmation bench-scale and pilot testing of column flotation have shown that advanced physical fine-coal cleaning procedures can be advantageously integrated into existing coal preparation plants. The following conclusions were drawn from this work:

- Column flotation can recover a lower-ash clean coal than the usual mechanical-cell flotation and at a higher recovery of combustibles. The following example is for the Lady Dunn application:
    - Microcel™ column – 10 to 11 percent ash clean coal, 75 percent recovery
    - Mechanical cells – 14 to 16 percent ash clean coal, 20 percent recovery
- Column flotation can be effectively applied to streams as coarse as minus 0.5 mm and, less effectively, to streams as coarse as minus 1.0 mm.
- High-pressure binderless bench-scale briquetting was effective for reconstituting the clean coal.
- Selective agglomeration performance projected from laboratory testing was similar to or somewhat better than the performance of column flotation.
- Projected near-term application costs for producing dewatered clean coal by column flotation of raw coal fines were in the $5.60 to $8.70 per dry short ton range.
- Projected near-term application costs for producing dewatered clean coal by selective agglomeration with a non-recoverable bridging liquid such as diesel fuel were significantly higher than the projected cost of recovering the clean coal by column flotation. Selective agglomeration was particularly less competitive with column flotation when cleaning midwestern Ayrshire coal which did not agglomerate as easily as the eastern Lady Dunn coal.
- Thermal drying the clean coal for blending with the existing plant production or for separate sale as powder fuel adds $7.60 to $10.60 per short ton to the production cost of the coal recovered by near-term advanced cleaning.
- The total projected cost of producing briquetted fuel (not including the cost of the raw coal fines) was less than $25.10 per short ton for four of the five near-term applications evaluated.

The following recommendations are offered to operators of coal preparation plants:

- Advanced physical fine coal cleaning options should be considered for installation in new plants and when refurbishing or expanding existing plants. It is likely that additional revenue can be generated over the revenues from the "no fine coal cleaning" or the "mechanical-cell flotation" options.

- In order to reduce costs, agglomeration with recoverable bridging liquids such as heptane and pentane, should be explored as alternatives to fuel oil and diesel fuel bridging liquids.
- Methods for improving the marketability of the recovered fine coal, such as GranuFlow processing, conversion to CWF, powder fuel, and especially binderless briquetting should be developed further.

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APPENDIX A

Tabulated Test Data

Table A-1. Washability of Ayrshire Fine Refuse

		Direct Product (Dry Basis)					Cumulative Float (Dry Basis)					Cumulative Sink (Dry Basis)			
Specific Gravity	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb
Plus 100 mesh -- 9.44%:											100.00	13.48	1.94	1.19	12,100
1.60	84.24	5.69	1.75	0.88	13,327	84.24	5.69	1.75	0.88	13,327	15.76	55.12	2.96	2.83	5,536
1.90	6.98	33.01	2.32	2.04	9,163	91.22	7.78	1.79	0.97	13,008	8.78	72.71	3.47	3.45	2,665
sink	8.78	72.71	3.47	3.45	2,665	100.00	13.48	1.94	1.19	12,100					
100x325 mesh -- 12.60%:											100.00	29.35	2.46	1.84	9,793
1.60	66.07	6.48	1.60	0.73	13,280	66.07	6.48	1.60	0.73	13,280	33.93	73.89	4.13	4.02	3,003
1.90	6.11	32.19	2.27	1.72	9,210	72.18	8.66	1.66	0.81	12,935	27.82	83.06	4.54	4.52	1,639
sink	27.82	83.06	4.54	4.52	1,639	100.00	29.35	2.46	1.84	9,793					
Minus 325 mesh -- 77.86%:											100.00	73.86	1.03	0.89	2,976
1.60	8.34	9.15	0.82	0.24	13,174	8.34	9.15	0.82	0.24	13,174	91.66	79.74	1.05	0.95	2,047
1.90	11.49	16.40	0.75	0.23	11,961	19.83	13.35	0.78	0.23	12,471	80.17	88.82	1.09	1.05	627
sink	80.17	88.82	1.09	1.05	627	100.00	73.86	1.03	0.89	2,976					
Composite As-Received Fine Refuse -- 100.00%:											100.00	62.55	1.30	1.04	4,696
1.60	22.78	6.97	1.43	0.64	13,266	22.78	6.97	1.43	0.64	13,266	77.22	78.95	1.26	1.15	2,168
1.90	10.38	18.63	0.96	0.46	11,579	33.17	10.62	1.28	0.58	12,738	66.83	88.32	1.30	1.26	705
sink	66.83	88.32	1.30	1.26	705	100.00	62.55	1.30	1.04	4,696					

Table A-2. Washability of Ayrshire Centrifuge Cake

	Direct Product (Dry Basis)					Cumulative Float (Dry Basis)					Cumulative Sink (Dry Basis)				
Specific Gravity	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb
Plus 100 mesh -- 89.70%:											100.00	22.45	2.70	1.87	10.650
1.60	74.09	8.74	2.17	1.14	12,782	74.09	8.74	2.17	1.14	12,782	25.91	61.64	4.21	3.95	4,554
1.90	8.65	35.14	2.98	2.32	8,618	82.74	11.50	2.25	1.26	12,347	17.26	74.91	4.83	4.77	2,517
sink	17.26	74.91	4.83	4.77	2,517	100.00	22.45	2.70	1.87	10,650					
100 mesh x 0 mesh -- 10.30%:											100.00	57.92	4.23	13.71	5,413
1.60	25.82	10.13	1.68	0.77	12,759	25.82	10.13	1.68	0.77	12,759	74.18	74.55	5.12	4.73	2,856
1.90	11.59	30.37	2.18	1.61	9,492	37.42	16.40	1.83	1.03	11,747	62.58	82.74	5.67	5.31	1,626
sink	62.58	82.74	5.67	5.31	1,626	100.00	57.92	4.23	3.71	5,413					
Composite As-Received Centrifuge Cake -- 100.00%:											100.00	26.10	2.86	2.06	10,110
1.60	69.12	8.79	2.15	1.13	12,781	69.12	64.83	2.15	1.13	12,781	30.88	64.83	4.44	4.15	4,133
1.90	8.95	34.50	2.87	2.23	8,735	78.07	77.21	2.23	1.25	12,317	21.93	77.21	5.08	4.93	2,255
sink	21.93	77.21	5.08	4.93	2,255	100.00	26.10	2.86	2.06	10,110					

Table A-3. Washability of Lady Dunn Vorsiv Underflow

		Direct Product (Dry Basis)					Cumulative Float (Dry Basis)					Cumulative Sink (Dry Basis)			
Specific Gravity	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb
Plus 100 mesh -- 16.93%:											100.00	15.34	0.87	0.19	12,498
1.60	84.22	7.05	0.86	0.11	13,874	84.22	7.05	0.86	0.11	13,874	15.78	59.56	0.95	0.63	5,155
1.90	7.58	40.87	0.78	0.40	8,163	91.80	9.84	0.85	0.13	13,403	8.20	76.83	1.11	0.85	2,375
sink	8.20	76.83	1.11	0.85	2,375	100.00	15.34	0.87	0.19	12,498					
100x325 mesh -- 22.65%:											100.00	20.46	0.95	0.34	11,667
1.60	72.57	6.19	0.84	0.08	14,018	72.57	6.19	0.84	0.08	14,018	27.43	58.22	1.25	1.04	5,446
1.90	9.96	27.28	0.76	0.29	10,394	82.53	8.73	0.83	0.11	13,581	17.47	75.85	1.53	1.47	2,626
sink	17.47	75.85	1.53	1.47	2,626	100.00	20.46	0.95	0.34	11,667					
Minus 325 mesh -- 60.43%:															
total	100.00	46.60	0.57	0.29	7,407										
Composite As-Received Fine Refuse -- 100.00%:															
		35.39	0.71	0.29	9,234										

Table A-4. Washability of Lady Dunn 28x100-mesh Stockton Coal

		Direct Product (Dry Basis)					Cumulative Float (Dry Basis)					Cumulative Sink (Dry Basis)			
Specific Gravity	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb	Weight %	Ash %	S(tot) %	S(pyr) %	HHV Btu/lb
28x100 mesh -- 100.00%:											100.00	30.56	0.94	0.42	10.044
1.60	62.92	10.72	0.85	0.14	13,353	62.92	10.72	0.85	0.14	13,353	37.08	64.22	1.08	0.89	4,429
1.90	13.66	39.33	0.84	0.42	8,526	76.58	15.82	0.85	0.19	12,492	23.42	78.73	1.22	1.16	2,040
sink	23.42	78.73	1.22	1.16	2,040	100.00	30.56	0.94	0.42	10,044					

Table A-5. Flotation of Ayrshire Fine Refuse in 2-inch Ken-Flote™ Column

Reagents: 2.0 lb/st Fuel Oil and 2.0 lb/st MIBC

Test	Feed kg/hr	Air std l/min	Wash Water, l/min	Solids Conc, %	Clean Coal Ash, %	Clean Coal Ash, lb/MBtu	Tailing Ash, %	Heating Value Recovery, %
6	6.0	4.0	0.4	10	9.50	7.06	90.63	95.5
7	6.0	4.0	0.6	10	8.40	6.16	85.25	78.4
8	6.0	4.0	0.8	10	8.00	5.84	85.38	78.8
9	6.0	4.0	0.1	10	12.30	9.47	85.07	78.2
10	6.0	4.0	0.0	10	13.89	13.81	86.40	82.9
11	6.0	6.0	0.4	10	9.96	7.45	92.29	99.7
12	6.0	7.0	0.4	10	10.80	7.27	90.17	94.1
13	6.0	3.0	0.4	10	9.27	6.87	89.74	92.8
15	9.0	4.0	0.4	10	11.27	8.57	88.27	88.4
16	16.0	4.0	0.4	10	12.25	9.43	86.99	84.4

Table A-6. Flotation of Lady Dunn Vorsiv Underflow in 2-inch Ken-Flote™ Column

Reagents: 0.5 lb/st Fuel Oil and 0.5 lb/st MIBC

Test	Feed kg/hr	Air std l/min	Wash Water, l/min	Solids Conc, %	Clean Coal Ash, %	Clean Coal Ash, lb/MBtu	Tailing Ash, %	Heating Value Recovery, %
A-1	5.34	4.0	0.4	8.9	9.60	7.15	86.36	97.1
A-2	5.34	5.0	0.4	8.9	10.40	7.82	85.67	96.8
A-3	5.34	2.0	0.4	8.9	5.40	3.82	84.06	95.2
A-4	5.34	4.0	0.6	8.9	6.54	4.69	80.92	88.9
A-5	5.34	4.0	0.8	8.9	5.69	4.04	57.82	64.0
A-6	5.34	4.0	0.2	8.9	7.90	5.76	89.81	94.9
A-7	4.0	4.0	0.6	8.9	5.30	3.75	83.18	62.2
A-8	8.0	4.0	0.6	8.9	4.53	3.18	44.08	23.6
A-9	10.6	4.0	0.6	8.9	4.35	3.04	39.76	14.2

Table A-7. Test Results 30-inch Microcel™ Test Series 101 - 110 (Cyclone Overflow

Test	Ash, %			Solids, %			Weight	Comb	Ash	Separation
	Feed	Conc	Tail	Feed	Conc	Ash, %	Yield, %	Rec, %	Rej, %	Eff, %
101	41.72	8.79	78.64	4.10	18.00	1.92	52.86	82.72	88.86	71.59
102	40.28	7.67	63.59	2.73	21.48	2.18	41.68	64.45	92.06	56.51
103	42.45	5.58	54.22	4.54	18.01	4.84	24.20	39.70	96.82	36.52
104	41.10	6.08	64.65	4.83	17.29	4.66	40.21	64.11	94.05	58.17
105	38.76	5.37	55.49	4.59	20.76	3.62	33.38	51.58	95.38	46.96
106	36.22	6.79	63.13	5.13	13.79	2.41	47.76	69.80	91.05	60.85
107	35.82	6.72	59.07	4.95	11.54	2.31	44.41	64.55	91.67	56.22
108	35.15	5.44	46.00	3.44	10.70	2.93	26.75	39.01	95.86	34.87
109	No Samples Analyzed									
110	39.89	6.73	55.45	3.75	11.43	2.69	31.94	49.56	94.61	44.17

Table A-8. Operating Parameters 30-inch Microcel™ Test Series 101 - 110 (Cyclone Overflow)

Test	Feed Rate, gpm	Feed Rate, kg/min	Conc Rate, kg/min	Conc Rate, Tph/m^2	Wash Water, gal/min	Air Meter, in H_2O	Air Rate, l/min	Air Rate, cm/s	Air Fraction, percent	Frother (glycol) ml/min	Collector (Diesel) ml/min	Collector g/T	Froth Depth, inches
101	60	9.6	5.1	0.67	14.0	24.0	416	1.5	32	?	0	0	
102	60	6.4	2.7	0.35	14.0	27.5	446	1.6	19	?	0	0	
103	60	10.6	2.6	0.34	14.0	25.8	432	1.6	23	?	0	0	
104	60	11.3	4.5	0.60	14.0	27.0	442	1.6	24	?	0	0	
105	44	7.9	2.6	0.35	14.0	27.0	442	1.6	22	?	0	0	
106	80	16.0	7.6	1.00	12.0	32.0	481	1.8	18	8.4	0	0	
107	110	21.2	9.4	1.24	12.0	42.0	551	2.0	19	9	0	0	
108	100	13.4	3.6	0.47	24.8	41.0	544	2.0	15	9.2	0	0	
109	100	0.0	0.0	0.00	19.8	41.0	544	2.0	?	10	0	0	
110	100	14.6	4.7	0.61	18.0	41.0	544	2.0	15	8	0	0	

Table A-9. Individual Results 30-inch Microcel™ Test Series 104 and 110

Test 104

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.500	0.05		40.49	0.03		5.72	0.09		61.93								
0.500x0.30	0.44	5.70	40.51	0.47	3.46	5.72	0.38	9.24	61.98	61.25	62.70	62.82	25.52	38.16	60.48	94.61	55.09
0.30x0.15	3.34	5.04	40.67	3.77	3.09	5.73	2.93	7.75	62.18	58.15	59.35	64.35	23.69	38.12	60.56	94.63	55.19
0.15x0.045	17.25	10.44	41.90	22.43	4.75	5.84	13.22	17.38	63.83	54.95	58.44	75.00	33.44	37.81	61.29	94.73	56.02
0.045x0	78.92	48.78	48.78	73.30	6.17	6.17	83.38	71.20	71.20	34.48	63.16	95.64	58.80	34.48	63.16	95.64	58.80
Cumulative	100.00	40.49		100.00	5.72		100.00	61.93		38.14	60.43	94.61	55.04				

Test 110

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.500																	
0.500x0.30	1.16	18.99	39.86	0.20	3.95	6.69	1.36	20.24	54.66	7.67	9.10	98.40	7.50	30.85	47.87	94.82	42.69
0.30x0.15	3.83	13.11	40.11	1.88	3.79	6.70	4.40	17.53	55.14	32.17	35.62	90.70	26.32	31.03	48.34	94.82	43.15
0.15x0.045	17.77	12.05	41.19	19.61	5.22	6.76	17.50	16.16	56.89	37.57	40.49	83.73	24.21	31.31	49.64	94.87	44.51
0.045x0	77.24	47.90	47.90	78.31	7.14	7.14	76.74	66.18	66.18	30.96	55.18	95.38	50.57	30.96	55.18	95.38	50.57
Cumulative	100.00	39.86		100.00	6.69		100.00	54.66		30.85	47.87	94.82	42.69				

Table A-10. Test Results 30-inch Microcel™ Test Series 201 - 215

Test	Ash, %			Solids, %				Wt Yield, %	Comb Rec, %	Ash Rej, %	Comb Sepn Eff, %
	Feed	Conc	Tails	Feed	Conc	Push Water	Tails				
201	46.66	7.63	62.15	5.56	9.09	Y	3.87	28.41	49.20	95.35	44.55
202	46.55	9.55	74.28	4.99	7.98	Y	2.66	42.84	72.49	91.21	63.71
203	42.52	7.19	63.47	4.61	9.14	Y	3.00	37.22	60.10	93.71	53.81
204	33.46	5.97	48.49	6.91	11.06	Y	4.50	35.35	49.95	93.69	43.64
205	33.43	8.69	66.99	7.75	15.31	Y	3.27	57.56	78.96	85.04	63.99
206	39.37	9.02	75.91	4.92	13.44	Y	2.20	54.63	81.97	87.48	69.46
207	40.10	8.62	68.41	5.96	10.58	Y	3.42	47.35	72.23	89.82	62.05
208	36.61	8.55	68.37	5.05	8.88	Y	2.72	53.09	76.59	87.60	64.20
209	35.51	8.82	69.19	5.59	6.94	Y	1.96	55.79	78.88	86.14	65.02
210	37.00	8.45	67.27	5.70	9.76	Y	3.04	51.46	74.78	88.25	63.03
211	33.67	6.83	68.30	4.71	10.31	Y	2.22	56.34	79.13	88.57	67.70
212	34.40	7.08	72.03	4.78	10.10	Y	2.08	57.94	82.07	88.08	70.14
213	35.33	7.85	73.65	4.44	9.52	Y	1.75	58.24	82.98	87.06	70.04
214	34.65	7.34	68.27	5.54	9.48	Y	2.31	55.18	78.24	88.31	66.55
215	35.50	8.14	63.68	5.05	9.96	Y	2.40	50.74	72.26	88.37	60.63

Table A-11. Operating Parameters 30-inch Microcel™ Test Series 201 - 215

Test	Feed Rate, gal/min	Feed Rate, kg/min	Conc Rate, kg/min	Wash Water, gal/min	Air Rate, cm/s	Air Fraction, percent	Frother ml/min	Collector (Diesel) ml/min	Collector g/T	Froth Depth, inches
201	100	21.7	6.2	12.2	2	16	8.7	0	0	25
202	100	19.4	8.3	12.2	2	23	11.6	0	0	25
203	120	21.5	8.0	15.4	2	19	11.6	0	0	25
204	80	21.5	7.6	13.9	2	17	8.8	0	0	27
205	60	18.1	10.4	14.4	2	23	7.5	0	0	27
206	80	15.3	8.4	18.0	2	19	9.6	18	641	24
207	100	23.2	11.0	18.0	2	17	9.6	18	405	22
208	115	22.6	12.0	18.0	2	18	11.2	18	624	24
209	100	21.8	12.1	18.0	2	17	10.8	18	564	22
210	100	22.2	11.4	18.0	1.5	12	10.8	18	553	25
211	100	18.3	10.3	20.0	2	17	7.9	18	641	29
212	100	18.6	10.8	20.0	2	17	9.2	27	948	29
213	100	17.3	10.1	20.0	2	17	9.2	36	1361	28
214	100	21.6	11.9	20.0	2	17	7.9	18	545	31
215	100	19.7	10.0	20.0	2	17	9.2	18	598	19

Table A-12. Individual Results 30-inch Microcel™ Test Series 203 - 215

Test 203

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	6.02	17.04	42.19	8.36	4.16	6.99	4.61	30.09	63.33	50.33	58.14	87.71	45.85	37.52	60.37	93.78	54.15
0.30x0.15	9.85	16.06	43.80	14.29	4.98	7.25	7.88	30.66	64.93	56.85	64.36	82.37	46.73	36.64	60.46	93.93	54.40
0.15x0.045	7.91	18.69	47.05	11.87	6.30	7.67	6.67	34.07	68.02	55.38	63.82	81.33	45.15	34.75	60.59	94.33	54.93
0.045x0	76.22	49.99	49.99	65.48	7.92	7.92	80.84	70.82	70.82	33.12	60.97	94.75	55.73	33.12	60.97	94.75	55.73
Cumulative	100.00	42.19		100.00	6.99		100.00	63.33		37.52	60.37	93.78	54.15				
Head Ash		42.52			7.19			63.47		37.22	60.10	93.71	53.81				

Test 204

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	30.46	9.46	32.46	23.35	3.57	5.78	29.28	13.66	48.00	41.63	44.33	84.29	28.62	36.80	51.34	93.45	44.80
0.30x0.15	11.02	17.62	42.54	14.58	5.36	6.45	9.92	28.34	62.22	46.65	53.59	85.81	39.40	35.29	57.46	94.65	52.11
0.15x0.045	6.31	25.15	47.23	9.45	6.38	6.70	6.09	40.55	67.75	45.07	56.37	88.57	44.94	33.61	59.43	95.23	54.66
0.045x0	52.21	49.90	49.90	52.62	6.76	6.76	54.71	70.78	70.78	32.61	60.70	95.58	56.28	32.61	60.70	95.58	56.28
Cumulative	100.00	32.46		100.00	5.78		100.00	48.00		36.81	51.35	93.45	44.79				
Head Ash		33.46			5.97			48.49		35.35	49.95	93.69	43.64				

Test 205

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.15	32.93	10.75	33.49	43.73	6.11	8.46	22.35	25.02	67.00	75.46	79.39	57.11	36.50	57.25	78.79	85.53	64.32
0.15x0.075	10.23	21.20	44.65	13.72	10.98	10.29	5.99	60.49	79.09	79.36	89.65	58.90	48.55	50.05	81.13	88.46	69.59
0.075x0.045	6.07	27.91	48.87	9.32	10.82	10.07	4.65	67.38	80.64	69.78	86.33	72.95	59.27	45.01	79.18	90.72	69.90
0.045x0	50.77	51.38	51.38	33.23	9.86	9.86	67.01	81.56	81.56	42.09	78.04	91.92	69.96	42.09	78.04	91.92	69.96
Cumulative	100.00	33.49		100.00	8.46		100.00	67.00		57.24	78.79	85.54	64.33				
Head Ash		33.43			8.69			66.99		57.56	78.96	85.04	63.99				

Table A-12 cont. Individual Results 30-inch Microcel™ Test Series 203 - 215

Test 206

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	0.86	12.78	39.55	1.61	6.78	8.72	0.64	31.48	75.99	75.71	80.92	59.84	40.75	54.17	81.80	88.06	69.85
0.30x0.15	4.24	14.64	39.78	8.39	7.59	8.75	1.32	56.51	76.27	85.59	92.66	55.63	48.28	54.05	81.90	88.11	70.01
0.15x0.045	15.91	15.93	40.90	30.97	8.38	8.86	6.27	55.76	76.54	84.07	91.61	55.78	47.39	52.66	81.21	88.59	69.80
0.045x0	78.99	45.93	45.93	59.03	9.11	9.11	91.77	77.96	77.96	46.52	78.20	90.77	68.97	46.52	78.20	90.77	68.97
Cumulative	100.00	39.55		100.00	8.72		100.00	75.99		54.17	81.80	88.06	69.85				
Head Ash		39.37			9.02			75.91		54.63	81.97	87.48	69.46				

Test 207

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.14	11.76	39.66	1.25	4.77	8.48	2.63	21.65	69.25	58.59	63.23	76.24	39.47	48.69	73.85	89.59	63.45
0.30x0.15	4.45	13.02	39.98	7.71	5.62	8.53	2.16	32.77	70.54	72.74	78.93	68.60	47.53	49.27	75.10	89.49	64.59
0.15x0.045	17.92	13.32	41.26	31.70	7.07	8.77	7.82	40.18	71.40	81.12	86.97	56.94	43.91	48.13	74.74	89.77	64.51
0.045x0	76.49	47.80	47.80	59.34	9.68	9.68	87.39	74.19	74.19	40.91	70.78	91.72	62.50	40.91	70.78	91.72	62.50
Cumulative	100.00	39.66		100.00	8.48		100.00	69.25		48.69	73.85	89.59	63.44				
Head Ash		40.10			8.62			68.41		47.35	72.23	89.82	62.05				

Test 208

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.27	12.11	37.88	1.59	6.11	8.41	0.89	21.37	67.86	60.68	64.82	69.38	34.21	50.43	74.36	88.80	63.16
0.30x0.15	4.85	13.04	38.21	9.17	5.92	8.45	1.96	36.64	68.28	76.82	83.11	65.12	48.24	50.26	74.46	88.89	63.35
0.15x0.045	19.21	14.52	39.51	33.06	7.04	8.71	8.28	39.92	68.92	77.25	84.01	62.55	46.56	48.84	73.71	89.24	62.95
0.045x0	74.67	45.94	45.94	56.18	9.69	9.69	88.87	71.62	71.62	41.47	69.27	91.25	60.53	41.47	69.27	91.25	60.53
Cumulative	100.00	37.88		100.00	8.41		100.00	67.86		50.43	74.35	88.80	63.16				
Head Ash		36.61			8.55			68.37		53.09	76.59	87.60	64.20				

Table A-12 cont. Individual Results 30-inch Microcel™ Test Series 203 - 215

Test 209

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.54	13.33	34.43	1.94	8.12	8.85	1.01	22.87	69.99	64.68	68.57	60.60	29.17	58.16	80.85	85.05	65.90
0.30x0.15	5.54	13.69	34.76	9.48	6.51	8.87	1.59	43.20	70.47	80.43	87.12	61.75	48.87	57.97	80.98	85.22	66.19
0.15x0.045	21.31	13.20	36.02	34.05	7.50	9.12	7.75	43.72	70.92	84.26	89.80	52.12	41.92	56.47	80.22	85.70	65.92
0.045x0	71.61	42.81	42.81	54.53	10.13	10.13	89.65	73.27	73.27	48.24	75.81	88.58	64.39	48.24	75.81	88.58	64.39
Cumulative	100.00	34.43		100.00	8.85		100.00	69.99		58.16	80.85	85.05	65.90				
Head Ash		35.51			8.82			69.19		55.79	78.88	86.14	65.02				

Test 210

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.36	12.78	37.87	2.22	6.14	8.28	0.90	27.68	68.07	69.17	74.44	66.77	41.21	50.51	74.56	88.96	63.52
0.30x0.15	5.30	13.49	38.22	10.28	7.32	8.33	1.84	48.35	68.44	84.96	91.02	53.90	44.92	50.27	74.60	89.05	63.64
0.15x0.045	20.20	14.65	39.62	33.26	7.54	8.45	7.92	42.97	68.82	79.93	86.59	58.86	45.45	48.36	73.33	89.69	63.02
0.045x0	73.14	46.52	46.52	54.24	9.00	9.00	89.34	71.11	71.11	39.59	67.37	92.34	59.71	39.59	67.37	92.34	59.71
Cumulative	100.00	37.87		100.00	8.28		100.00	68.07		50.51	74.57	88.96	63.52				
Head Ash		37.00			8.45			67.27		51.46	74.78	88.25	63.03				

Test 211

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.14	7.54	33.67	1.25	4.54	6.83	0.72	13.53	68.30	66.63	68.79	59.88	28.67	56.34	79.13	88.57	67.71
0.30x0.15	5.10	8.16	33.97	8.58	4.96	6.86	1.61	24.66	68.69	83.76	86.67	49.09	35.76	56.16	79.22	88.66	67.88
0.15x0.045	21.87	10.62	35.37	34.45	6.08	7.04	8.86	37.45	69.42	85.53	89.87	51.04	40.91	54.58	78.51	89.14	67.65
0.045x0	71.89	42.90	42.90	55.72	7.63	7.63	88.81	72.61	72.61	45.72	73.96	91.87	65.83	45.72	73.96	91.87	65.83
Cumulative	100.00	33.67		100.00	6.83		100.00	68.30		56.34	79.13	88.57	67.70				

Table A-12 cont. Individual Results 30-inch Microcel™ Test Series 203 - 215

Test 212

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.27	9.01	34.40	1.86	4.79	7.08	0.84	18.69	72.03	69.64	72.87	62.98	35.85	57.94	82.07	88.07	70.14
0.30x0.15	5.89	11.39	34.72	10.63	5.88	7.12	1.77	38.59	72.48	83.15	88.33	57.07	45.40	57.77	82.20	88.15	70.34
0.15x0.045	20.79	11.92	36.20	39.36	6.56	7.28	7.58	45.78	73.09	86.33	91.59	52.49	44.07	56.05	81.46	88.74	70.20
0.045x0	72.05	43.21	43.21	48.15	7.86	7.86	89.81	75.40	75.40	47.66	77.33	91.33	68.66	47.66	77.33	91.33	68.66
Cumulative	100.00	34.40		100.00	7.08		100.00	72.03		57.94	82.07	88.08	70.14				

Test 213

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.47	9.36	35.33	1.78	5.34	7.85	0.77	19.15	73.65	70.89	74.03	59.56	33.59	58.23	82.98	87.06	70.04
0.30x0.15	5.75	11.43	35.72	9.63	6.05	7.89	1.63	42.71	74.07	85.32	90.51	54.84	45.34	57.95	83.04	87.19	70.23
0.15x0.045	22.42	13.77	37.23	32.49	7.12	8.10	7.13	49.05	74.60	84.14	90.63	56.49	47.12	56.20	82.27	87.78	70.05
0.045x0	70.36	44.70	44.70	56.10	8.66	8.66	90.47	76.61	76.61	46.96	77.57	90.90	68.47	46.96	77.57	90.90	68.47
Cumulative	100.00	35.33		100.00	7.85		100.00	73.65		58.24	82.98	87.06	70.04				

Test 214

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	1.20	9.67	34.65	1.57	5.41	7.34	1.10	17.06	68.27	63.43	66.43	64.51	30.94	55.18	78.24	88.31	66.55
0.30x0.15	5.91	12.08	34.95	10.27	5.24	7.37	2.45	31.62	68.84	74.07	79.83	67.87	47.70	55.13	78.51	88.37	66.88
0.15x0.045	21.21	13.65	36.41	33.14	6.43	7.62	9.37	40.00	69.79	78.49	85.06	63.03	48.08	53.70	78.00	88.76	66.76
0.045x0	71.68	43.14	43.14	55.02	8.34	8.34	87.08	72.99	72.99	46.17	74.43	91.07	65.50	46.17	74.43	91.07	65.50
Cumulative	100.00	34.65		100.00	7.34		100.00	68.27		55.18	78.24	88.31	66.55				

Table A-12 cont. Individual Results 30-inch Microcel™ Test Series 203 - 215

Test 215

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	0.98	8.16	35.50	1.30	4.85	8.14	1.42	18.13	63.88	75.08	77.78	55.38	33.16	50.92	72.51	88.32	60.83
0.30x0.15	4.94	9.57	35.77	8.35	4.97	8.19	3.24	25.07	64.54	77.11	81.04	59.95	40.99	51.05	72.97	88.32	61.29
0.15x0.045	20.14	12.01	37.14	30.65	6.33	8.48	10.43	32.47	65.88	78.27	83.32	58.75	42.07	50.06	72.89	88.56	61.46
0.045x0	73.94	43.99	43.99	59.70	9.59	9.59	84.91	69.98	69.98	43.04	69.47	90.62	60.09	43.04	69.47	90.62	60.09
Cumulative	100.00	35.50		100.00	8.14		100.00	63.88		50.91	72.51	88.33	60.84				

Table A-13. Test Results 30-inch Microcel™ Test Series 301 - 302

Test	Ash , percent			Solids, percent				Wt Yield, %	Comb Rec, %	Ash Rej, %	Comb Sepn Eff, %
	Feed	Clean Coal	Tails	Feed	Clean Coal	Add Push Water	Tails				
301	38.88	8.25	55.52	5.97	10.76	N	3.23	35.20	52.84	92.53	45.37
302	40.23	12.47	59.17	7.91	9.55	N	2.50	40.56	59.39	87.43	46.82

Table A-14. Operation Parameters 30-inch Microcel™ Test Series 301 - 302

Test	Feed Rate, gal/min	Feed Rate, kg/min	Conc Rate, kg/min	Conc Rate, Tph/m^2	Wash Water, gal/min	Air Rate, l/min	Air Rate, cm/s	Air Fraction, percent	Frother, ml/min	Collector (Diesel), ml/min	Coll. g/T	Feed Sump, gal/min	Froth Depth, inches
301	100	23.3	8.2	1.08	14.4	544	2.0	22	10.5	0	0	110	20
302	100	30.8	12.5	1.64	14.4	544	2.0	18	7	25	579	110	26

Table A-15. Individual Results 30-inch Microcel™ Test Series 301 - 302

Test 301

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	3.51	16.47	38.88	2.44	3.26	8.25	4.12	17.35	55.52	6.25	7.23	98.76	6.00	35.19	52.83	92.53	45.36
0.30x0.15	10.42	16.80	39.70	14.48	4.64	8.38	9.35	22.75	57.16	32.85	37.66	90.93	28.58	35.79	54.38	92.45	46.83
0.15x0.045	21.76	23.50	42.47	30.84	7.36	9.03	19.75	29.55	60.88	27.26	33.02	91.46	24.48	35.50	56.13	92.46	48.59
0.045x0	64.31	48.89	48.89	52.24	10.01	10.01	66.78	70.14	70.14	35.34	62.22	92.76	54.99	35.34	62.22	92.76	54.99
Cumulative	100.00	38.88		100.00	8.25		100.00	55.52		35.20	52.84	92.53	45.37				

Test 302

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	3.57	16.20	39.21	1.24	4.83	10.54	4.82	18.44	58.01	16.46	18.69	95.09	13.78	39.61	58.29	89.35	47.64
0.30x0.15	11.11	19.11	40.06	8.91	4.85	10.61	12.15	26.31	60.02	33.55	39.47	91.49	30.95	40.39	60.23	89.30	49.54
0.15x0.045	22.00	24.49	42.79	28.40	7.12	11.18	20.02	42.35	64.95	50.70	62.36	85.26	47.62	41.21	63.98	89.23	53.21
0.045x0	63.32	49.15	49.15	61.45	13.06	13.06	63.01	72.13	72.13	38.90	66.51	89.66	56.18	38.90	66.51	89.66	56.18
Cumulative	100.00	39.21		100.00	10.54		100.00	58.01		39.60	58.28	89.35	47.64				

Table A-16. Test Results 30-inch Microcel™ First Parametric Test Series 401 - 416

Test	Total Ash, percent			Solids, percent			Wt Yield, %	Comb Rec, %	Ash Rej, %	Comb Sepn Eff, %
	Feed	Conc	Tails	Feed	Conc	Tails				
401	34.36	12.06	52.65	7.96	13.40	5.60	45.06	60.37	84.18	44.55
402	36.07	9.47	58.54	7.62	15.77	4.88	45.79	64.84	87.98	52.82
403	40.67	9.03	60.75	11.22	11.95	6.62	38.82	59.53	91.38	50.91
404	36.76	8.51	48.11	13.73	12.63	10.00	28.66	41.47	93.36	34.83
405	38.50	10.73	72.58	7.11	16.79	5.02	55.10	79.98	84.64	64.62
406	39.85	10.64	58.34	17.23	17.51	7.73	38.76	57.59	89.65	47.24
407	41.40	11.67	68.07	11.93	21.53	6.93	47.29	71.28	86.67	57.95
408	41.00	8.86	51.37	14.33	13.00	8.70	24.39	37.68	94.73	32.41
409	37.92	8.84	50.42	9.97	12.95	8.52	30.06	44.14	92.99	37.14
410	40.21	9.48	55.41	10.07	15.68	6.46	33.09	50.10	92.20	42.30
411	41.91	8.80	54.59	12.98	12.13	8.40	27.69	43.48	94.19	37.66
412	39.65	9.71	55.22	10.69	13.87	9.04	34.21	51.19	91.62	42.81
413	39.99	13.91	50.96	14.52	9.80	10.88	29.61	42.48	89.70	32.18
414	44.65	12.64	71.30	9.09	16.42	5.62	45.43	71.71	87.14	58.84
415	46.02	11.70	66.51	10.38	18.60	5.00	37.38	61.15	90.50	51.65
416	43.62	12.57	69.22	7.44	17.73	5.85	45.19	70.08	86.98	57.05

Table A-17. Operating Parameters 30-inch Microcel™ First Parametric Tests Series 401 - 416

Test	Feed Rate, gal/min	Feed Rate, kg/min	Conc Rate, kg/min	Conc Rate Tph/m²	Conc Rate, -.5 mm	Wash Water, l/min	Air Rate, l/min	Air Rate, cm/s	Air Fraction, percent	Frother, ml/min	Collect (Diesel,, ml/min	Coll. g/T	Coll. -.5 mm, g/T	Feed Sump, gal/min	Froth Depth, inches
401	100	31.0	14.0	1.84		48	544	2.0	17	10.5	30	690	920	110	24
402	100	29.7	13.6	1.79		68	465	1.7	15	11.6	30	721	961	110	28
403	100	43.7	17.0	2.23	2.00	68	425	1.6	17	11.6	30	518	696	104	28
404	80	42.8	12.3	1.61	1.55	55	425	1.6	20	11.6	30	423	552	104	24
405	80	22.2	12.2	1.61	1.32	55	425	1.6	13	11.6	48	1307	1805	104	28
406	60	40.3	15.6	2.05	1.78	55	425	1.6	13	24	48	539	753	104	30
407	60	27.9	13.2	1.73	1.32	55	425	1.6	17	10	30	487	707	104	28
408	80	44.7	10.9	1.43	1.41	68	425	1.6	18	10	15	201	254	105	26
409	100	38.8	11.7	1.54	1.49	68	425	1.6	?	11	18	346	445	105	22
410	100	39.2	13.0	1.71	1.60	68	425	1.6	?	11	30	571	745	105	24
411	90	45.5	12.6	1.66	1.61	68	425	1.6	?	11	30	405	530	115	26
412	103	42.9	14.7	1.93	1.74	82	425	1.6	?	10	40	731	1007	103	Turb
413	80	45.2	13.4	1.76	1.63	68	408	1.5	?	10	30	520	758		32
414	80	28.3	12.9	1.69	1.35	67	408	1.5	?	8	30	831	1249		32
415	80	32.3	12.1	1.59	1.29	65	425	1.6	?	8	45	1091	1521		32
416	95	27.5	12.4	1.64	1.38	64	425	1.6	?	8	45	1282	2020		32

Table A-18. Individual Results 30-inch Microcel™ Test Series 401 - 416

Test 401

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	35.44	29.30	34.36	17.32	6.28	12.06	51.57	36.23	52.65	23.14	30.67	95.04	25.71	45.06	60.36	84.18	44.54
0.30x0.15	13.42	32.22	37.14	21.45	11.32	13.27	11.65	57.93	70.13	55.16	72.17	80.62	52.79	58.03	80.05	79.26	59.31
0.15x0.045	16.26	25.68	38.43	28.16	12.22	13.96	10.17	65.90	73.99	74.93	88.50	64.35	52.84	59.24	82.78	78.48	61.26
0.045x0	34.88	44.37	44.37	33.07	15.44	15.44	26.61	77.08	77.08	53.07	80.66	81.53	62.20	53.07	80.66	81.53	62.20
Cumulative	100.00	34.36		100.00	12.06		100.00	52.65		45.06	60.37	84.18	44.55				

Test 402

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+0.30	38.02	30.09	36.07	25.97	6.13	9.47	47.36	41.92	58.54	33.05	44.38	93.27	37.65	45.79	64.85	87.98	52.83
0.30x0.15	14.54	37.40	39.74	22.19	10.23	10.64	12.16	66.43	73.49	51.65	74.07	85.87	59.95	53.71	79.64	85.62	65.26
0.15x0.045	16.38	32.45	40.45	25.99	11.19	10.81	10.20	70.43	75.61	64.11	84.29	77.89	62.18	54.26	81.27	85.50	66.77
0.045x0	31.06	44.67	44.67	25.85	10.43	10.43	30.28	77.36	77.36	48.84	79.07	88.60	67.66	48.84	79.07	88.60	67.66
Cumulative	100.00	36.07		100.00	9.47		100.00	58.54		45.79	64.84	87.98	52.82				

Test 403

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.25	36.23	40.67	0.13	6.07	9.03	4.96	42.18	60.75	16.48	24.27	97.24	21.51	38.82	59.53	91.38	50.91
1.00x0.50	22.42	32.59	40.82	10.10	4.07	9.04	25.43	38.78	61.72	17.83	25.38	97.77	23.15	39.67	60.98	91.22	52.20
0.50x0.25	13.94	40.68	43.30	16.19	6.80	9.59	12.08	54.43	70.10	28.87	45.36	95.17	40.53	44.29	70.62	90.19	60.81
0.25x0.15	10.57	43.59	43.91	14.67	9.17	10.21	7.39	64.82	73.39	38.15	61.43	91.97	53.40	46.66	74.70	89.15	63.85
0.15x0.045	16.76	34.30	43.98	27.63	9.91	10.47	10.90	64.12	74.65	55.01	75.43	84.11	59.54	47.80	76.38	88.62	65.01
0.045x0	33.06	48.88	48.88	31.28	10.96	10.96	39.24	77.58	77.58	43.08	75.04	90.34	65.38	43.08	75.04	90.34	65.38
Cumulative	100.00	40.67		100.00	9.03		100.00	60.75		38.82	59.53	91.38	50.91				

Table A-18 cont. Individual Results 30-inch Microcel™ Test Series 401 - 416

Test 404

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.05	29.85	36.76	0.07	18.74	8.51	5.52	31.37	48.11	12.03	13.94	92.44	6.39	28.67	41.47	93.36	34.83
1.00x0.50	20.26	27.18	36.98	4.09	3.23	8.51	28.21	28.87	49.09	6.59	8.76	99.22	7.98	29.85	43.33	93.13	36.46
0.50x0.25	13.28	33.34	39.57	12.79	4.75	8.73	13.64	37.41	57.70	12.46	17.81	98.22	16.03	37.03	55.92	91.83	47.75
0.25x0.15	10.18	35.95	40.87	13.62	7.47	9.34	7.58	42.65	62.95	19.04	27.51	96.04	23.56	41.20	63.16	90.58	53.74
0.15x0.045	16.61	29.44	41.81	28.49	8.75	9.71	11.06	49.56	66.37	49.30	63.76	85.35	49.10	43.35	67.26	89.93	57.19
0.045x0	36.62	47.42	47.42	40.94	10.38	10.38	33.99	71.84	71.84	39.73	67.72	91.30	59.03	39.73	67.72	91.30	59.03
Cumulative	100.00	36.76		100.00	8.51		100.00	48.11		28.66	41.47	93.36	34.83				

Test 405

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	4.72	34.06	38.50	0.50	2.89	10.73	5.67	49.35	72.58	32.91	48.47	97.21	45.67	55.10	79.98	84.64	64.62
1.00x0.50	22.86	31.44	38.72	17.51	5.28	10.77	26.36	55.63	73.97	48.04	66.38	91.93	58.31	55.78	81.22	84.48	65.70
0.50x0.25	14.53	37.88	41.02	17.58	9.98	11.95	12.68	75.49	81.09	57.41	83.20	84.87	68.07	57.95	86.52	83.12	69.64
0.25x0.15	10.68	39.97	41.81	14.58	14.11	12.48	8.06	83.94	82.37	62.97	90.09	77.77	67.86	58.04	87.29	82.67	69.96
0.15x0.045	16.86	36.40	42.23	23.25	13.08	12.01	11.00	82.32	82.11	66.32	90.64	76.17	66.81	56.89	86.65	83.82	70.47
0.045x0	30.37	45.46	45.46	26.58	11.07	11.07	36.23	82.04	82.04	51.54	84.04	87.45	71.49	51.54	84.04	87.45	71.49
Cumulative	100.00	38.50		100.00	10.73		100.00	72.58		55.10	79.98	84.64	64.62				

Test 406

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.66	37.28	39.85	0.30	3.71	10.84	6.88	38.74	58.34	4.17	6.40	99.59	5.98	38.92	57.69	89.41	47.10
1.00x0.50	24.68	34.27	39.95	13.08	4.67	10.87	32.96	38.13	59.79	11.54	16.73	98.43	15.16	40.55	60.19	88.97	49.16
0.50x0.25	15.20	34.90	41.91	17.43	8.30	11.80	13.75	54.66	71.66	42.62	60.04	89.86	49.90	49.70	75.46	86.01	61.46
0.25x0.15	10.20	37.13	43.80	13.22	11.91	12.68	8.00	69.12	76.69	55.92	78.35	82.06	60.41	51.39	79.84	85.12	64.96
0.15x0.045	15.53	36.89	45.27	22.25	12.13	12.87	9.67	73.15	78.27	59.42	82.74	80.46	63.20	50.46	80.33	85.66	65.99
0.045x0	30.73	49.50	49.50	33.72	13.35	13.35	28.74	79.99	79.99	45.75	78.51	87.66	66.17	45.75	78.51	87.66	66.17
Cumulative	100.00	39.85		100.00	10.84		100.00	58.34		38.93	57.70	89.41	47.11				

Table A-18 cont. Individual Results 30-inch Microcel™ Test Series 401 - 416

Test 407

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	6.87	40.56	41.40	0.76	3.01	11.67	9.02	50.59	68.07	21.08	34.40	98.44	32.83	47.28	71.27	86.68	57.95
1.00x0.50	24.27	35.88	41.46	22.98	6.09	11.73	27.78	54.61	69.80	38.60	56.54	93.45	49.99	48.80	73.59	86.19	59.78
0.50x0.25	14.92	38.86	43.43	16.60	11.24	13.44	13.58	64.57	76.48	48.21	69.99	86.06	56.04	52.42	80.22	83.78	64.00
0.25x0.15	9.98	40.16	44.70	13.93	15.99	14.05	7.24	71.13	79.74	56.17	78.85	77.64	56.49	53.34	82.91	83.24	66.14
0.15x0.045	14.50	37.23	45.73	20.73	15.81	13.45	8.92	75.89	81.21	64.35	86.31	72.67	58.98	52.37	83.51	84.59	68.10
0.045x0	29.46	49.91	49.91	25.00	11.50	11.50	33.46	82.63	82.63	46.00	81.27	89.40	70.68	46.00	81.27	89.40	70.68
Cumulative	100.00	41.40		100.00	11.67		100.00	68.07		47.29	71.28	86.67	57.95				

Test 408

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.04	36.06	41.00	0.01	24.31	8.86	4.61	37.56	51.37	11.32	13.40	92.37	5.77	24.40	37.69	94.72	32.42
1.00x0.50	17.78	35.09	41.15	1.92	11.38	8.86	26.64	38.08	52.04	11.20	15.29	96.37	11.66	25.21	39.05	94.57	33.62
0.50x0.25	16.58	37.85	42.52	14.08	5.18	8.81	15.21	39.61	57.45	5.11	7.80	99.30	7.10	30.70	48.70	93.64	42.34
0.25x0.15	9.43	35.75	43.75	14.73	7.44	9.42	7.73	46.24	62.52	27.04	38.95	94.37	33.32	35.34	56.91	92.39	49.30
0.15x0.045	15.39	31.28	45.17	29.34	8.79	9.84	11.12	45.65	65.26	38.99	51.74	89.04	40.79	36.25	59.61	92.10	51.71
-0.045x0	37.78	50.83	50.83	39.92	10.62	10.62	34.69	71.55	71.55	34.01	61.82	92.90	54.71	34.01	61.82	92.90	54.71
Cumulative	100.00	41.00		100.00	8.86		100.00	51.37		24.39	37.68	94.73	32.41				

Test 409

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.41	32.30	37.92	0.39	22.82	8.84	7.86	29.23	50.42	0.00	0.00	0.00	0.00	30.06	44.14	92.99	37.13
1.00x0.50	18.81	29.67	38.12	2.90	4.96	8.79	29.64	31.46	52.23	6.75	9.13	98.87	8.00	32.48	47.87	92.51	40.38
0.50x0.25	16.17	31.18	40.16	16.65	5.52	8.90	16.66	43.01	62.07	31.56	43.32	94.41	37.73	41.21	62.74	90.87	53.60
0.25x0.15	9.25	26.66	42.52	14.73	7.71	9.61	6.34	54.33	69.00	59.35	74.69	82.84	57.52	44.59	70.12	89.93	60.05
0.15x0.045	14.79	26.24	45.32	27.96	9.18	10.03	8.78	57.35	71.36	64.58	79.52	77.41	56.93	42.46	69.86	90.60	60.46
0.045x0	37.57	52.83	52.83	37.37	10.67	10.67	30.72	75.36	75.36	34.83	65.96	92.97	58.92	34.83	65.96	92.97	58.92
Cumulative	100.00	37.92		100.00	8.84		100.00	50.42		30.06	44.14	92.99	37.14				

Table A-18 cont. Individual Results 30-inch Microcel™ Test Series 401 - 416

Test 410

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	4.15	33.49	40.21	0.08	6.26	9.48	8.15	36.5	55.41	9.95	14.03	98.14	12.17	33.09	50.10	92.20	42.30
1.00x0.50	19.20	33.80	40.50	6.04	3.83	9.48	30.47	36.53	57.09	8.35	12.13	99.05	11.18	34.84	53.01	91.85	44.85
0.50x0.25	18.86	37.21	42.18	20.95	6.71	9.84	14.84	51.40	67.30	31.75	47.18	94.27	41.45	43.71	68.16	89.80	57.96
0.25x0.15	9.28	36.13	43.81	14.76	10.34	10.74	6.42	62.98	72.37	51.01	71.60	85.40	57.01	46.35	73.62	88.64	62.25
0.15x0.045	14.53	29.67	45.28	27.17	10.69	10.84	7.94	59.98	73.87	61.49	78.09	77.84	55.93	45.37	73.92	89.13	63.05
0.045x0	33.98	51.95	51.95	31.00	10.98	10.98	32.18	77.30	77.30	38.22	70.82	91.92	62.74	38.22	70.82	91.92	62.74
Cumulative	100.00	40.21		100.00	9.48		100.00	55.41		33.09	50.10	92.20	42.30				

Test 411

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	4.12	33.61	41.91	0.03	14.71	8.80	5.57	35.93	54.59	10.93	14.05	95.21	9.26	27.68	43.46	94.19	37.65
1.00x0.50	19.59	35.50	42.27	2.62	3.74	8.79	24.4	39.02	55.69	9.98	14.89	98.95	13.84	28.62	45.21	94.05	39.26
0.50x0.25	16.86	42.34	44.01	14.72	5.35	8.93	16.26	45.92	61.49	8.82	14.49	98.88	13.37	33.27	54.11	93.25	47.36
0.25x0.15	8.93	35.48	44.48	14.63	8.08	9.57	7.55	51.46	66.20	36.84	52.48	91.61	44.09	38.36	62.48	91.75	54.23
0.15x0.045	14.30	28.80	46.07	31.47	9.06	9.89	10.06	49.97	68.61	51.75	66.09	83.72	49.82	38.39	64.14	91.76	55.91
0.045x0	36.20	52.89	52.89	36.52	10.60	10.60	36.16	73.80	73.80	33.09	62.79	93.37	56.15	33.09	62.79	93.37	56.15
Cumulative	100.00	41.91		99.99	8.80		100.00	54.59		27.69	43.48	94.19	37.66				

Test 412

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	5.92	37.41	39.65	0.23	8.51	9.71	9.47	42.34	55.22	14.57	21.30	96.68	17.99	34.21	51.18	91.62	42.80
1.00x0.50	21.41	29.09	39.79	9.57	5.81	9.71	25.26	41.42	56.56	34.63	45.99	93.08	39.08	35.80	53.68	91.26	44.94
0.50x0.25	10.78	31.82	42.94	13.03	5.62	10.13	10.45	46.89	62.42	36.52	50.55	93.55	44.10	37.25	58.67	91.21	49.89
0.25x0.15	8.67	30.88	44.88	10.97	5.81	10.89	6.56	47.34	65.38	39.63	54.01	92.54	46.55	37.62	60.83	90.87	51.70
0.15x0.045	14.09	27.90	47.16	24.66	6.58	11.73	9.69	47.09	67.84	47.37	61.38	88.83	50.21	36.85	61.56	90.83	52.39
0.045x0	39.13	54.10	54.10	41.54	14.79	14.79	38.57	73.05	73.05	32.53	60.38	91.11	51.49	32.53	60.38	91.11	51.49
Cumulative	100.00	39.65		100.00	9.71		100.00	55.22		34.21	51.19	91.62	42.81				

Table A-18 cont. Individual Results 30-inch Microcel™ Test Series 401 - 416

Test 413

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	5.01	38.69	39.99	0.16	7.00	13.91	6.75	36.88	50.96	na	na	na	na	29.61	42.48	89.70	32.18
1.00x0.50	26.36	33.71	40.06	7.58	5.18	13.93	26.77	35.82	51.98	6.89	9.85	98.94	8.79	31.33	44.99	89.11	34.10
0.50x0.25	10.65	35.77	42.50	12.84	5.20	14.64	11.51	40.81	58.49	14.15	20.89	97.94	18.83	36.47	54.14	87.43	41.57
0.25x0.15	8.61	31.78	43.74	11.54	5.44	16.17	7.75	43.74	62.19	31.23	43.28	94.65	37.94	40.10	59.75	85.17	44.92
0.15x0.045	13.97	27.55	45.82	23.00	6.53	17.99	10.94	43.93	65.22	43.80	56.50	89.62	46.12	41.08	62.18	83.87	46.04
0.045x0	35.40	53.03	53.03	44.88	23.87	23.87	36.28	71.64	71.64	38.96	63.14	82.46	45.61	38.96	63.14	82.46	45.61
Cumulative	100.00	39.99		100.00	13.91		100.00	50.96		29.61	42.48	89.70	32.18				

Test 414

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	7.53	44.54	44.65	0.40	3.04	12.84	8.9	50.93	71.30	13.34	23.33	99.09	22.42	45.58	71.78	86.90	58.68
1.00x0.50	25.98	42.45	44.66	19.91	5.62	12.88	27.7	56.93	73.29	28.22	46.28	96.26	42.54	47.39	74.61	86.34	60.95
0.50x0.25	11.63	39.41	45.53	16.46	11.13	14.69	9.99	71.72	80.44	53.33	78.22	84.94	63.16	53.10	83.16	82.87	66.03
0.25x0.15	8.35	36.80	46.83	12.74	15.01	15.61	5.15	76.82	82.07	64.75	87.07	73.59	60.66	53.04	84.17	82.31	66.48
0.15x0.045	12.38	29.23	48.63	22.33	15.41	15.77	6.87	73.32	82.63	76.14	91.00	59.86	50.86	50.86	83.39	83.51	66.90
-0.045x0	34.13	55.66	55.66	28.16	16.05	16.05	41.39	84.18	84.18	41.86	79.26	87.93	67.19	41.86	79.26	87.93	67.19
Cumulative	100.00	44.65		100.00	12.84		100.00	71.30		45.59	71.79	86.89	58.68				

Test 415

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	5.66	38.84	46.02	0.42	3.66	11.70	10.66	46.49	66.51	17.86	28.14	98.32	26.45	37.39	61.16	90.50	51.66
1.00x0.50	22.60	43.04	46.45	18.36	5.95	11.73	33.24	52.96	68.90	21.10	34.84	97.08	31.93	39.27	64.73	90.08	54.82
0.50x0.25	13.20	45.32	47.52	16.30	11.21	13.04	10.12	68.47	78.35	40.43	65.65	90.00	55.65	47.20	78.21	87.05	65.27
0.25x0.15	9.17	39.95	48.02	12.65	11.95	13.49	5.05	74.73	80.52	55.40	81.23	83.43	64.66	48.49	80.70	86.37	67.07
0.15x0.045	12.90	30.97	49.52	22.51	13.31	13.87	6.77	72.95	81.24	70.39	88.40	69.75	58.15	47.08	80.33	86.81	67.15
0.045x0	36.47	56.08	56.08	29.76	14.29	14.29	34.16	82.88	82.88	39.07	76.25	90.04	66.29	39.07	76.25	90.04	66.29
Cumulative	100.00	46.02		100.00	11.70		100.00	66.51		37.38	61.15	90.50	51.65				

Table A-18 cont. Individual Results 30-inch Microcel™ Test Series 401 - 416

Test 416

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	11.71	42.25	43.26	0.32	4.17	12.57	10.71	46	69.22	8.96	14.88	99.12	13.99	45.84	70.62	86.68	57.30
1.00x0.50	24.83	42.44	43.39	15.40	5.85	12.60	27.37	54.35	72.01	24.56	40.17	96.62	36.78	48.17	74.37	86.01	60.38
0.50x0.25	11.76	39.94	43.76	15.66	11.77	13.83	9.72	71.46	79.81	52.81	77.57	84.44	62.01	54.64	83.72	82.73	66.44
0.25x0.15	8.27	34.18	44.63	13.36	12.30	14.30	4.64	78.18	81.37	66.79	88.99	75.97	64.96	54.78	84.78	82.44	67.23
0.15x0.045	12.64	29.21	46.62	23.89	14.25	14.79	5.80	73.10	81.68	74.58	90.34	63.62	53.96	52.41	83.67	83.37	67.04
0.045x0	30.79	53.77	53.77	31.37	15.20	15.20	41.76	82.87	82.87	43.00	78.88	87.84	66.72	43.00	78.88	87.84	66.72
Cumulative	100.00	43.26		100.00	12.57		100.00	69.22		45.83	70.61	86.68	57.30				

Table A-19. Test Results 30-inch Microcel™ Second Parametric Tests Series 451 - 465

Test	Ash, percent			Solids, percent			Wt Yield, %	Comb Rec, %	Ash Rej, %	Comb Sepn Eff, %
	Feed	Conc	Tails	Feed	Conc	Tails				
451	36.95	11.18	67.83	7.32	12.35	3.11	54.50	76.79	83.52	60.30
452	38.62	11.24	69.13	7.06	15.40	5.23	52.71	76.22	84.66	60.88
453	36.29	11.23	67.32	8.27	12.73	3.40	55.31	77.08	82.89	59.97
454	34.26	11.43	66.05	6.76	12.31	2.33	58.20	78.42	80.59	59.00
455	33.87	10.08	66.29	7.31	15.90	2.76	57.68	78.43	82.84	61.26
456	35.63	11.12	51.39	7.35	14.55	11.38	39.14	54.04	87.78	41.82
457	42.61	10.60	66.45	14.18	12.32	6.28	42.69	66.50	89.38	55.88
458	34.70	9.33	56.41	13.16	15.57	7.64	46.10	64.02	87.61	51.63
459	38.86	10.66	68.06	13.43	12.01	7.44	50.88	74.34	86.05	60.39
460	40.24	11.52	68.43	10.10	15.51	5.75	49.54	73.35	85.81	59.16
461	42.80	11.78	72.56	9.19	14.17	3.86	48.97	75.52	86.52	62.03
462	36.31	12.63	69.73	12.24	10.47	4.81	58.53	80.29	79.64	59.93
463	45.02	12.08	75.53	13.24	17.25	8.66	48.10	76.90	87.09	63.99
464	42.44	12.60	74.06	10.08	11.50	4.90	51.44	78.11	84.74	62.85
465	42.30	12.68	75.10	13.90	13.77	6.32	52.55	79.52	84.25	63.77

Table A-20. Operating Parameters 30-inch Microcel™ Second Parametric Tests Series 451 - 465

Test	Feed Rate, gal/min	Feed Rate, kg/min	Conc Rate, kg/min	Conc Rat, Tph/m^2	Conc Rate -.5 mm	Wash Wate,r l/min	Air Rate, l/min	Air Rate, cm/s	Air Fraction, percent	Frother, ml/min	Collect (Diesel), ml/min	Coll. g/T	Coll., -.5 mm g/T	Froth Depth, inches
451	41	11.7	6.4	0.84	0.73	54.6	323	1.2	5.0	4.5	16.5	1107	1358	24
452	60	16.5	8.7	1.14	1.03	47.8	350	1.3	3.5	7.3	24	1141	1383	20
453	50	16.1	8.9	1.17	1.02	40.9	306	1.1	3.5	9.3	20	974	1171	26
454	50	13.2	7.7	1.01	0.87	43.7	350	1.3	2.0	9.3	20	1191	1445	24
455	50	14.2	8.2	1.08	0.98	43.7	350	1.3	3.3	5.5	20	1102	1348	28
456	60	17.2	6.7	0.88	0.83	43.7	329	1.2	3.3	11.0	24	1096	1385	25
457	50	27.6	11.8	1.55	1.38	51.8	329	1.2	11.0	8.0	20	568	699	29
458	50	25.6	11.8	1.55	1.37	51.8	329	1.2	11.9	8.0	20	612	765	30
459	50	26.2	13.3	1.75	1.54	47.8	306	1.1	9.3	6.0	20	600	749	27
460	60	23.6	11.7	1.54	1.37	47.8	306	1.1	10.0	9.0	23	764	1041	28
461	40	14.3	7.0	0.92	0.76	47.8	306	1.1	11.0	6.0	16	876	1128	25
462	60	28.6	16.7	2.20	1.90	54.6	329	1.2	9.5	6.3	23	631	745	27
463	40	20.6	9.9	1.31	1.04	50.5	350	1.3	12.9	6.0	16	608	834	25
464	40	15.7	8.1	1.06	0.86	50.5	329	1.2	13.6	7.5	16	799	1136	25
465	50	27.1	14.2	1.87	1.66	50.5	329	1.2	11.3	7.5	19	550	724	28

Table A-21. Individual Results 30-inch Microcel™ Test Series 451 - 465

Test 451

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	1.98	20.70	36.95	0.75	4.33	11.18	1.9	30.05	67.83	36.35	43.86	92.40	36.25	54.50	76.79	83.52	60.30
1.00x0.50	16.48	23.66	37.28	11.63	5.32	11.23	13.21	35.35	68.56	38.93	48.28	91.25	39.53	54.56	77.22	83.57	60.79
0.50x0.25	19.14	34.31	40.04	24.84	10.02	12.01	12.96	54.39	73.73	45.26	61.99	86.78	48.77	54.60	80.11	83.62	63.73
0.25x0.15	9.69	34.51	41.79	13.64	13.59	12.80	8.28	74.13	77.22	65.44	86.35	74.23	60.58	54.99	82.38	83.16	65.54
0.15x0.045	16.74	32.43	43.13	23.48	13.50	12.58	13.05	73.04	77.62	68.21	87.31	71.61	58.92	53.03	81.51	84.53	66.05
0.045x0	35.97	48.11	48.11	25.66	11.74	11.74	50.60	78.80	78.80	45.76	77.84	88.83	66.67	45.76	77.84	88.83	66.67
Cumulative	100.00	36.96		100.00	11.18		100.00	67.83		54.49	76.78	83.52	60.29				

Test 452

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	1.40	24.21	38.62	0.21	3.24	11.24	2.00	40.59	69.13	43.86	55.99	94.13	50.12	52.71	76.22	84.66	60.88
1.00x0.50	16.11	26.61	38.82	9.99	4.96	11.26	22.06	52.73	69.72	54.68	70.81	89.81	60.62	52.85	76.66	84.68	61.34
0.50x0.25	20.97	37.98	41.21	23.04	9.06	11.96	17.92	67.12	74.65	50.19	73.59	88.03	61.62	53.34	79.88	84.52	64.41
0.25x0.15	11.22	39.35	42.30	12.35	13.13	12.95	9.73	74.80	76.97	57.48	82.33	80.82	63.15	54.16	81.70	83.42	65.12
0.15x0.045	16.84	34.07	42.96	24.82	13.10	12.92	10.57	71.00	77.41	63.78	84.07	75.48	59.54	53.41	81.55	83.94	65.49
0.045x0	33.46	47.44	47.44	29.59	12.76	12.76	37.72	79.21	79.21	47.81	79.36	87.14	66.50	47.81	79.36	87.14	66.50
Cumulative	100.00	38.62		100.00	11.24		100.00	69.13		52.70	76.21	84.66	60.87				

Test 453

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	1.38	20.21	36.29	0.58	3.54	11.23	1.69	24.30	67.32	19.70	23.82	96.55	20.37	55.31	77.08	82.89	59.97
1.00x0.50	15.44	24.09	36.52	12.64	5.69	11.27	13.06	36.31	68.06	39.91	49.58	90.57	40.16	55.54	77.63	82.86	60.49
0.50x0.25	19.51	38.33	38.82	19.05	9.55	12.08	14.47	58.52	72.92	41.23	60.47	89.73	50.20	56.05	80.55	82.55	63.10
0.25x0.15	11.78	38.07	38.98	13.75	13.34	12.80	9.39	73.97	75.87	59.21	82.86	79.25	62.11	58.49	83.58	80.79	64.38
0.15x0.045	16.14	29.37	39.18	22.79	12.85	12.66	12.70	71.04	76.16	71.61	88.36	68.67	57.03	58.23	83.62	81.19	64.81
0.045x0	35.75	43.61	43.61	31.19	12.52	12.52	48.69	77.49	77.49	52.15	80.90	85.03	65.93	52.15	80.90	85.03	65.93
Cumulative	100.00	36.29		100.00	11.23		100.00	67.32		55.32	77.08	82.88	59.96				

Table A-21 Cont. Individual Results 30-inch Microcel™ Test Series 451 - 465

Test 454

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	1.67	22.88	34.26	0.75	4.35	11.43	1.95	24.82	66.05	9.48	11.75	98.20	9.95	58.20	78.42	80.59	59.00
1.00x0.50	15.90	23.81	34.45	12.67	5.70	11.48	13.36	29.31	66.87	23.30	28.83	94.42	23.26	58.53	79.04	80.50	59.54
0.50x0.25	17.05	30.19	36.51	20.05	9.18	12.33	12.62	54.77	72.80	53.92	70.14	83.61	53.75	60.02	82.87	79.73	62.61
0.25x0.15	11.36	32.11	38.15	14.65	13.62	13.27	6.46	67.78	75.96	65.86	83.80	72.06	55.86	60.31	84.57	79.02	63.59
0.15x0.045	17.33	30.37	39.42	24.80	13.95	13.18	10.89	71.25	76.76	71.34	88.17	67.23	55.40	58.72	84.17	80.37	64.54
0.045x0	36.69	43.70	43.70	27.08	12.47	12.47	54.72	77.86	77.86	52.24	81.22	85.09	66.31	52.24	81.22	85.09	66.31
Cumulative	100.00	34.25		100.00	11.43		100.00	66.05		58.22	78.43	80.57	59.00				

Test 455

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	1.61	20.51	33.87	0.50	3.47	10.08	2.04	22.25	66.29	9.27	11.25	98.43	9.68	57.68	78.43	82.84	61.26
1.00x0.50	16.66	23.50	34.09	8.49	5.25	10.11	14.67	32.25	67.21	32.41	40.14	92.76	32.90	58.01	79.11	82.79	61.90
0.50x0.25	18.25	28.48	36.24	14.03	8.68	10.56	14.61	57.48	73.36	59.43	75.88	81.89	57.77	59.11	82.91	82.77	65.69
0.25x0.15	9.56	29.50	38.48	8.03	11.90	10.91	6.38	66.45	76.74	67.74	84.65	72.68	57.32	58.12	84.17	83.52	67.69
0.15x0.045	16.04	26.20	40.07	12.93	11.67	10.79	10.53	71.28	77.79	75.62	90.51	66.32	56.83	56.31	83.81	84.83	68.64
0.045x0	37.88	45.94	45.94	56.02	10.59	10.59	51.77	79.12	79.12	48.42	80.08	88.84	68.92	48.42	80.08	88.84	68.92
Cumulative	100.00	33.87		100.00	10.08		100.00	66.29		57.68	78.43	82.83	61.26				

Test 456

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	2.05	25.47	35.63	0.14	6.60	11.12	2.05	26.72	51.39	6.21	7.79	98.39	6.18	39.14	54.04	87.78	41.82
1.00x0.50	18.84	26.60	35.84	5.95	3.85	11.13	21.50	29.06	51.90	9.76	12.78	98.59	11.37	39.39	54.57	87.77	42.33
0.50x0.25	19.98	33.25	38.04	16.62	5.99	11.59	17.56	41.03	58.33	22.20	31.27	96.00	27.27	43.40	61.93	86.78	48.71
0.25x0.15	9.97	30.93	39.66	13.07	7.46	12.79	9.94	50.95	63.48	46.03	61.68	88.90	50.57	47.00	67.93	84.84	52.76
0.15x0.045	16.41	29.22	41.43	26.13	8.40	13.88	13.77	50.98	66.03	51.10	66.14	85.31	51.45	47.17	69.36	84.20	53.55
0.045x0	32.75	47.55	47.55	38.09	17.64	17.64	35.18	71.92	71.92	44.90	70.50	83.34	53.84	44.90	70.50	83.34	53.84
Cumulative	100.00	35.63		100.00	11.12		100.00	51.39		39.14	54.04	87.79	41.82				

Table A-21 cont. Individual Results 30-inch Microcel™ Test Series 401 - 415

Test 457

Particle	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
Size, mm	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	1.51	33.92	42.61	0.35	3.43	10.60	2.03	35.09	66.45	3.70	5.40	99.63	5.03	42.69	66.50	89.38	55.88
1.00x0.50	17.25	35.16	42.74	10.54	4.66	10.62	15.58	35.89	67.10	2.34	3.44	99.69	3.13	43.13	67.32	89.28	56.60
0.50x0.25	19.66	43.18	44.35	21.47	8.76	11.33	12.73	57.15	73.00	28.87	46.36	94.14	40.50	46.46	74.02	88.13	62.16
0.25x0.15	11.12	41.43	44.72	12.93	11.14	12.14	7.09	67.85	75.90	46.59	70.68	87.47	58.15	48.90	77.72	86.72	64.44
0.15x0.045	17.34	35.06	45.45	22.98	10.31	12.38	11.25	62.63	76.81	52.69	72.78	84.50	57.28	48.67	78.18	86.74	64.92
0.045x0	33.12	50.89	50.89	31.73	13.88	13.88	51.32	79.92	79.92	43.96	77.09	88.01	65.10	43.96	77.09	88.01	65.10
Cumulative	100.00	42.61		100.00	10.60		100.00	66.45		42.69	66.49	89.38	55.88				

Test 458

Particle	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
Size, mm	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	2.19	26.65	34.70	0.40	4.98	9.33	2.77	29.66	56.41	12.20	15.80	97.72	13.52	46.10	64.02	87.61	51.63
1.00x0.50	17.77	25.53	34.88	11.48	4.87	9.34	23.88	29.06	57.17	14.59	18.64	97.22	15.86	46.60	64.88	87.52	52.39
0.50x0.25	18.07	28.93	36.96	19.78	7.48	9.92	12.69	41.70	66.32	37.32	48.58	90.35	38.93	52.06	74.39	86.02	60.41
0.25x0.15	8.68	29.27	39.30	11.45	9.49	10.63	7.01	57.20	71.47	58.54	74.91	81.02	55.93	52.88	77.85	85.69	63.55
0.15x0.045	15.17	26.54	40.93	23.07	9.75	10.86	11.12	58.47	73.33	65.54	80.52	75.92	56.44	51.87	78.27	86.24	64.51
0.045x0	38.12	46.66	46.66	33.85	11.62	11.62	42.53	77.22	77.22	46.59	77.19	88.40	65.59	46.59	77.19	88.40	65.59
Cumulative	100.00	34.70		100.03	9.33		100.00	56.41		46.11	64.03	87.60	51.63				

Test 459

Particle	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
Size, mm	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	2.09	28.19	38.86	0.50	6.31	10.66	2.89	36.85	68.06	28.36	37.00	93.65	30.65	50.88	74.34	86.05	60.39
1.00x0.50	17.80	30.23	39.08	11.43	5.17	10.68	20.05	47.54	68.99	40.85	55.53	93.01	48.54	51.29	75.20	85.99	61.19
0.50x0.25	17.42	33.40	41.05	24.84	9.06	11.39	19.06	68.05	74.57	58.74	80.21	84.07	64.27	53.06	79.75	85.27	65.03
0.25x0.15	8.87	34.37	43.18	12.17	10.28	12.31	8.32	73.34	76.72	61.80	84.48	81.52	66.00	52.08	80.36	85.15	65.51
0.15x0.045	15.52	30.36	44.63	22.83	11.39	12.79	10.56	68.47	77.28	66.77	84.95	74.95	59.90	50.64	79.75	85.48	65.23
0.045x0	38.30	50.41	50.41	28.23	13.93	13.93	39.12	79.66	79.66	44.50	77.24	87.70	64.94	44.50	77.24	87.70	64.94
Cumulative	100.00	38.86		100.00	10.66		100.00	68.06		50.87	74.33	86.05	60.38				

Table A-21 cont. Individual Results 30-inch Microcel™ Test Series 451 - 465

Test 460

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.74	35.81	40.24	0.55	4.44	11.52	1.66	38.05	68.43	6.66	9.92	99.17	9.10	49.54	73.35	85.81	59.16
1.00x0.50	22.84	40.13	40.41	10.15	5.45	11.56	13.97	44.79	68.94	11.85	18.71	98.39	17.10	49.73	73.80	85.77	59.57
0.50x0.25	17.48	35.43	40.49	20.49	9.64	12.25	16.97	67.04	72.94	55.07	77.07	85.02	62.08	53.47	78.84	83.82	62.66
0.25x0.15	12.48	34.85	42.08	14.27	12.17	13.03	9.11	71.24	74.43	61.60	83.05	78.49	61.54	52.70	79.12	83.68	62.79
0.15x0.045	14.47	31.93	44.15	25.22	12.49	13.26	11.79	66.31	74.93	63.88	82.12	75.01	57.14	49.91	77.51	85.01	62.52
0.045x0	28.99	50.25	50.25	29.32	13.92	13.92	46.50	77.11	77.11	42.51	73.55	88.23	61.77	42.51	73.55	88.23	61.77
Cumulative	100.00	40.24		100.00	11.52		100.00	68.43		49.53	73.34	85.82	59.16				

Test 461

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	2.89	27.90	42.80	1.29	4.86	11.78	2.55	34.72	72.56	22.84	30.14	96.02	26.16	48.97	75.52	86.52	62.03
1.00x0.50	19.39	34.34	43.24	16.09	6.00	11.87	13.74	48.93	73.55	33.99	48.65	94.06	42.72	49.14	76.30	86.51	62.80
0.50x0.25	22.07	46.52	45.46	23.13	10.39	13.02	10.62	69.64	77.59	39.02	65.38	91.28	56.67	49.76	79.35	85.75	65.10
0.25x0.15	10.58	48.46	45.04	13.01	14.75	14.04	40.02	77.41	78.74	46.20	76.42	85.94	62.36	52.09	81.47	83.76	65.23
0.15x0.045	14.97	34.59	44.23	21.94	14.41	13.84	5.52	74.66	80.35	66.51	87.02	72.29	59.32	54.30	83.90	83.01	66.91
0.045x0	30.10	49.03	49.03	24.54	13.33	13.33	27.55	81.49	81.49	47.62	80.98	87.05	68.03	47.62	80.98	87.05	68.03
Cumulative	100.00	42.80		100.00	11.78		100.00	72.56		48.96	75.52	86.52	62.04				

Test 462

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	2.35	29.50	36.31	0.79	4.62	12.63	2.44	31.30	69.73	6.75	9.13	98.94	8.07	58.53	80.29	79.64	59.93
1.00x0.50	13.03	21.22	36.47	12.97	6.40	12.69	10.95	33.79	70.69	45.89	54.53	86.16	40.68	59.00	81.09	79.47	60.55
0.50x0.25	15.38	20.32	38.82	23.06	10.98	13.64	7.54	53.30	75.36	77.93	87.06	57.89	44.96	59.20	83.57	79.20	62.77
0.25x0.15	8.98	24.66	42.93	12.92	12.63	14.61	5.67	67.70	77.46	78.16	90.63	59.97	50.61	54.94	82.20	81.30	63.51
0.15x0.045	18.67	29.58	45.65	23.09	12.85	15.12	10.81	68.00	78.22	69.66	86.22	69.74	55.95	51.61	80.60	82.91	63.51
0.045x0	41.59	52.87	52.87	27.17	17.05	17.05	62.59	79.98	79.98	43.08	75.82	86.11	61.93	43.08	75.82	86.11	61.93
Cumulative	100.00	36.31		100.00	12.63		100.00	69.73		58.53	80.29	79.64	59.93				

Table A-21 cont. Individual Results 30-inch Microcel™ Test Series 451 - 465

Test 463

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.28	40.07	45.02	1.19	4.72	12.08	8.37	66.47	75.53	42.75	67.97	94.96	62.94	48.10	76.90	87.09	63.99
1.00x0.50	23.78	43.45	45.19	19.41	7.03	12.17	41.06	70.57	76.36	42.68	70.17	93.09	63.26	48.57	77.82	86.91	64.74
0.50x0.25	17.17	45.50	45.75	19.08	10.50	13.43	16.98	79.09	81.07	48.97	80.42	88.70	69.12	52.21	83.32	84.67	67.99
0.25x0.15	10.35	41.99	45.83	11.40	13.31	14.36	5.79	82.36	82.06	58.46	87.37	81.47	68.84	53.52	84.61	83.23	67.84
0.15x0.045	14.54	35.07	46.70	21.42	13.14	14.60	6.05	78.74	82.00	66.57	89.05	75.06	64.11	52.37	83.92	83.63	67.54
0.045x0	30.88	52.18	52.18	27.50	15.74	15.74	21.75	82.91	82.91	45.75	80.61	86.20	66.81	45.75	80.61	86.20	66.81
Cumulative	100.00	45.02		100.00	12.08		100.00	75.53		48.09	76.89	87.10	63.99				

Test 464

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	4.43	45.61	42.44	0.96	3.96	12.60	4.50	52.03	74.06	13.36	23.58	98.84	22.42	51.44	78.11	84.74	62.85
1.00x0.50	25.23	43.77	42.30	18.13	6.15	12.68	23.23	60.68	75.10	31.01	51.76	95.64	47.40	52.55	79.52	84.25	63.77
0.50x0.25	16.95	35.62	41.77	21.11	11.33	14.14	12.86	70.25	79.73	58.77	80.95	81.30	62.25	57.88	85.34	80.40	65.74
0.25x0.15	9.20	39.06	43.72	13.21	15.15	15.14	4.85	77.46	81.78	61.63	85.81	76.10	61.90	57.11	86.12	80.23	66.35
0.15x0.045	14.53	32.92	44.69	20.80	15.16	15.13	8.72	77.74	82.17	71.62	90.58	67.02	57.60	55.90	85.78	81.07	66.85
0.045x0	29.66	50.46	50.46	25.79	15.11	15.11	45.84	83.01	83.01	47.94	82.15	85.65	67.79	47.94	82.15	85.65	67.79
Cumulative	100.00	42.44		100.00	12.60		100.00	74.06		51.45	78.12	84.73	62.85				

Test 465

Particle Size, mm	Feed, percent			Clean Coal, percent			Tailings, percent			Individual by Size, percent				Cum From Bottom, percent			
	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt	Ash	Cum Ash	Wt Yield	Comb Rec	Ash Rej	Sepn Eff	Wt Yield	Comb Rec	Ash Rej	Sepn Eff
+1.00	3.39	38.27	40.99	0.54	4.48	11.36	5.82	57.12	70.10	35.81	55.41	95.81	51.22	49.55	74.43	86.27	60.70
1.00x0.50	20.62	36.40	41.09	10.62	5.88	11.40	23.05	54.38	70.90	37.07	54.86	94.01	48.87	50.10	75.35	86.10	61.45
0.50x0.25	18.48	38.32	42.36	16.93	9.80	12.06	11.09	63.09	76.25	46.48	67.97	88.11	56.09	52.80	80.55	84.97	65.52
0.25x0.15	9.98	38.06	43.66	12.37	10.90	12.59	5.85	71.79	78.68	55.39	79.69	84.14	63.82	52.99	82.21	84.72	66.93
0.15x0.045	14.63	30.44	44.83	26.49	11.00	12.94	9.70	71.97	79.42	68.12	87.15	75.39	62.54	52.03	82.11	84.98	67.09
0.045x0	32.90	51.23	51.23	33.05	14.49	14.49	44.49	81.05	81.05	44.80	78.55	87.33	65.88	44.80	78.55	87.33	65.88
Cumulative	100.00	40.99		100.00	11.36		100.00	70.10		49.56	74.44	86.27	60.71				

Table A-22. PSD of Dried Briquetter Feed Coal

	Weight, percent	
Mesh	Retained	Passing
4	0.00	100.00
8	0.00	100.00
16	0.58	99.42
28	9.00	90.42
48	23.52	66.90
60	6.05	60.85
100	13.85	47.00
150	8.88	38.12
200	6.42	31.70
Pan	31.70	100.00

APPENDIX B

Design Expert Analysis of Lady Dunn Flotation Results

Table B-1. First Series (401-416) 0.25 mm x 0

Response: 0.25 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed Rate	kg/min	Numeric	25.00	45.00
B	Frother	ml/min	Numeric	8.00	12.00
C	Diesel	g/ton -.5mm	Numeric	200.00	2000.00

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	87165.18	1	87165.18		
Linear	1308.93	3	436.31	21.11	< 0.0001
Quadratic	157.68	6	26.28	1.75	0.2578
Cubic	90.36	6	15.06		
Residual	0.000	0			
Total	88722.14	16	5545.13		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	4.55	0.8407	0.8009	0.6635	523.93
Quadratic	3.88	0.9420	0.8549	0.0804	1431.81
Cubic					

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-1 cont.

Response: 0.25 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed Rate	kg/min	Numeric	25.00	45.00
B	Frother	ml/min	Numeric	8.00	12.00
C	Diesel	g/ton -.5mm	Numeric	200.00	2000.00

ANOVA for Response Surface Quadratic Model:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1466.60	9	162.96	10.82	0.0045
Residual	90.36	6	15.06		
Cor Total	1556.96	15			

Root MSE	3.88	R-Squared	0.9420	
Dep Mean	73.81	Adj R-Squared	0.8549	
C.V.	5.26	Pred R-Squared	0.0804	
PRESS	1431.81	Adeq Precision	9.914	Desire > 4

Factor	Coefficient Estimate	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|	VIF
Intercept	77.95	1	3.66			
A-Feed Rate	-12.42	1	3.56	-3.49	0.0130	7.60
B-Frother	4.27	1	2.80	1.52	0.1787	7.22
C-Diesel	5.32	1	5.97	0.89	0.4067	10.53
A^2	-4.38	1	5.59	-0.78	0.4637	5.73
B^2	-1.09	1	1.24	-0.88	0.4140	7.22
C^2	-0.50	1	11.14	-0.045	0.9658	12.02
AB	10.70	1	6.78	1.58	0.1655	15.53
AC	-0.42	1	9.90	-0.042	0.9677	13.43
BC	7.05	1	11.69	0.60	0.5684	23.90

Response: 0.25 mm x 0 Rec. - Final Equation in Terms of Coded Factors:

0.25x0 Rec. =

+77.95
-12.42 * A
+4.27 * B
+5.32 * C
-4.38 * A^2

Table B-1 cont.

$-1.09 * B^2$
$-0.50 * C^2$
$+10.70 * A * B$
$-0.42 * A * C$
$+7.05 * B * C$

Response: 0.25 mm x 0 Rec. - Final Equation in Terms of Actual Factors:

0.25x0 Rec. =
+240.61
-3.48 * Feed Rate
-15.47 * Frother
-0.030 * Diesel
-0.044 * Feed Rate^2
-0.27 * Frother^2
-6.154E-07 * Diesel^2
+0.53 * Feed Rate * Frother
-4.646E-05 * Feed Rate * Diesel
+3.917E-03 * Frother * Diesel

Response: 0.25 mm x 0 Rec. -- Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	74.70	69.14	5.56	0.411	1.867	0.243	2.634	3
2	70.12	69.90	0.22	0.388	0.072	0.000	0.065	9
3	84.17	85.87	-1.70	0.853	-1.139	0.750	-1.174	14
4	87.29	87.14	0.15	0.960	0.199	0.096	0.182	5
5	80.05	80.67	-0.62	0.258	-0.186	0.001	-0.171	1
6	82.91	82.01	0.90	0.904	0.748	0.524	0.717	7
7	79.64	79.74	-0.10	0.718	-0.050	0.001	-0.045	2
8	73.62	72.57	1.05	0.393	0.347	0.008	0.320	10
9	56.91	56.72	0.19	0.798	0.108	0.005	0.099	8
10	80.70	77.65	3.05	0.521	1.134	0.140	1.168	15
11	84.78	85.51	-0.73	0.906	-0.610	0.357	-0.575	16
12	60.83	64.88	-4.05	0.640	-1.742	0.540	-2.262	12
13	63.16	68.33	-5.17	0.301	-1.594	0.109	-1.916	4
14	79.84	79.98	-0.14	0.995	-0.522	5.399	-0.488	6
15	59.75	58.79	0.96	0.501	0.349	0.012	0.321	13
16	62.48	62.04	0.44	0.454	0.155	0.002	0.142	11

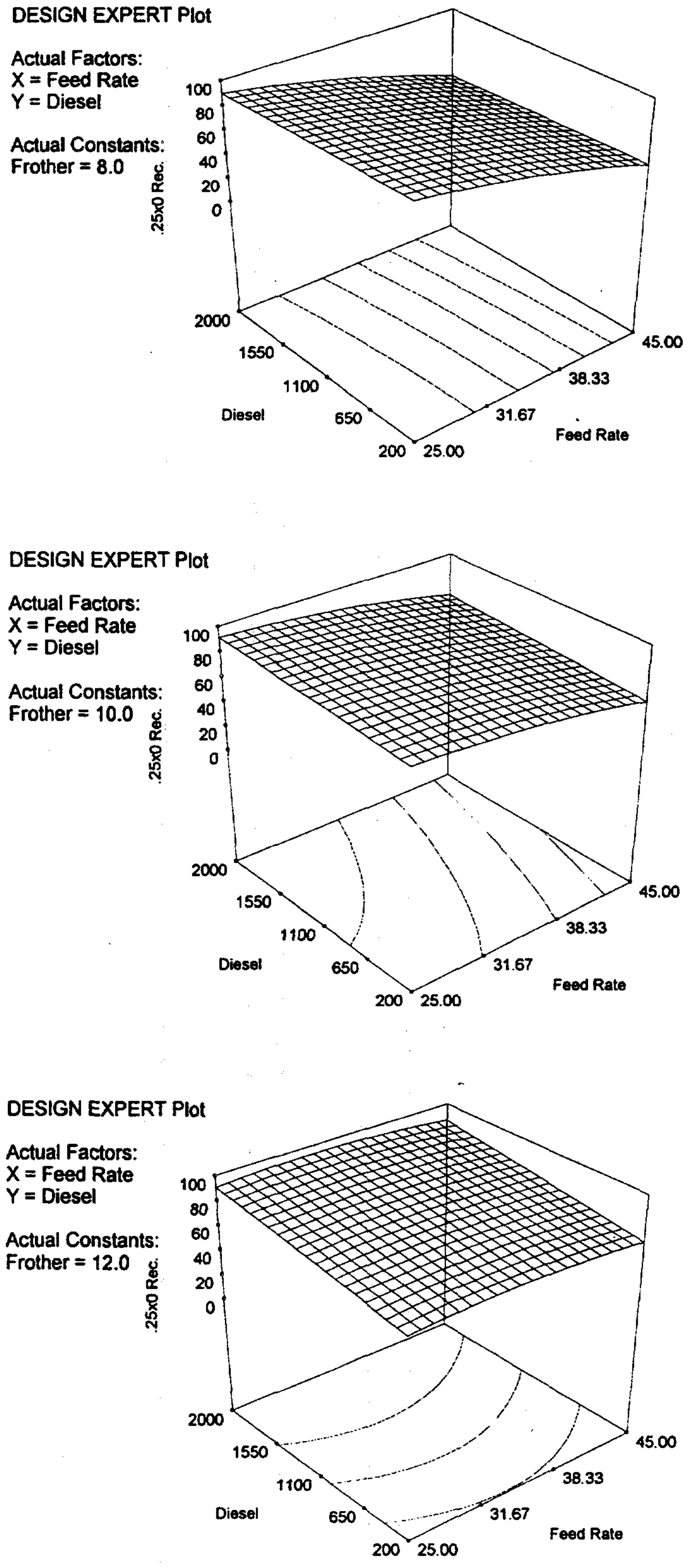


Figure B-1. 3D Response Plots, First Series (401-416) 0.25 mm x 0 Recovery

Table B-2. First Series (401-416) 0.50 x 0.25 mm

Response: 0.50 x 0.25 mm Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed Rate	kg/min	Numeric	25.00	45.00
B	Frother	ml/min	Numeric	8.00	12.00
C	Diesel	g/ton -.5mm	Numeric	200.00	2000.00

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	40307.59	1	40307.59		
Linear	7184.16	3	2394.72	19.95	< 0.0001
Quadratic	1171.56	6	195.26	4.36	0.0480
Cubic	268.52	6	44.75		
Residual	0.000	0			
Total	48931.83	16	3058.24		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	10.95	0.8330	0.7913	0.6434	3075.81
Quadratic	6.69	0.9689	0.9222	0.0011	8614.65
Cubic					

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-2 cont.

Response: 0.50 x 0.25 mm Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed Rate	kg/min	Numeric	25.00	45.00
B	Frother	ml/min	Numeric	8.00	12.00
C	Diesel	g/ton -.5mm	Numeric	200.00	2000.00

ANOVA for Response Surface Quadratic Model:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	8355.72	9	928.41	20.75	0.0007
Residual	268.52	6	44.75		
Cor Total	8624.24	15			

Root MSE	6.69	R-Squared	0.9689	
Dep Mean	50.19	Adj R-Squared	0.9222	
C.V.	13.33	Pred R-Squared	0.0011	
PRESS	8614.65	Adeq Precision	14.232	Desire > 4

Factor	Coefficient Estimate	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|	VIF
Intercept	72.02	1	6.31			
A-Feed Rate	-7.26	1	6.13	-1.18	0.2814	7.60
B-Frother	11.01	1	4.83	2.28	0.0628	7.22
C-Diesel	42.91	1	10.29	4.17	0.0059	10.53
A^2	-14.87	1	9.64	-1.54	0.1738	5.73
B^2	-0.42	1	2.13	-0.20	0.8491	7.22
C^2	41.28	1	19.21	2.15	0.0752	12.02
AB	34.05	1	11.68	2.91	0.0268	15.53
AC	42.71	1	17.07	2.50	0.0464	13.43
BC	58.59	1	20.15	2.91	0.0271	23.90

Response: 0.50 x 0.25 mm Rec - Final Equation in Terms of Coded Factors:

0.50x0.25 Rec. =
+72.02
-7.26 * A
+11.01 * B
+42.91 * C

Table B-2 cont.

$-14.87 * A^2$
$-0.42 * B^2$
$+41.28 * C^2$
$+34.05 * A * B$
$+42.71 * A * C$
$+58.59 * B * C$

Response: 0.50 x 0.25 mm Rec - Final Equation in Terms of Actual Factors:

0.50x0.25 Rec. =
+995.35
-12.56 * Feed Rate
-87.76 * Frother
-0.56 * Diesel
-0.15 * Feed Rate^2
-0.11 * Frother^2
+5.096E-05 * Diesel^2
+1.70 * Feed Rate * Frother
+4.745E-03 * Feed Rate * Diesel
+0.033 * Frother * Diesel

Response: 0.50 x 0.25 mm Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	45.36	38.02	7.34	0.411	1.429	0.142	1.606	3
2	43.32	36.49	6.83	0.388	1.306	0.108	1.409	9
3	78.22	75.38	2.84	0.853	1.105	0.706	1.130	14
4	83.20	83.45	-0.25	0.960	-0.188	0.085	-0.172	5
5	60.00	65.42	-5.42	0.258	-0.941	0.031	-0.931	1
6	69.99	72.05	-2.06	0.904	-0.992	0.922	-0.990	7
7	61.00	56.41	4.59	0.718	1.292	0.424	1.388	2
8	47.18	49.77	-2.59	0.393	-0.496	0.016	-0.463	10
9	7.80	8.18	-0.38	0.798	-0.127	0.006	-0.116	8
10	65.65	66.96	-1.31	0.521	-0.283	0.009	-0.260	15
11	77.57	77.56	8.544E-03	0.906	0.004	0.000	0.004	16
12	50.55	49.53	1.02	0.640	0.255	0.012	0.234	12
13	17.81	27.45	-9.64	0.301	-1.723	0.128	-2.214	4
14	60.04	60.46	-0.42	0.995	-0.882	15.370	-0.862	6
15	20.89	22.24	-1.35	0.501	-0.287	0.008	-0.263	13
16	14.49	13.70	0.79	0.454	0.159	0.002	0.145	11

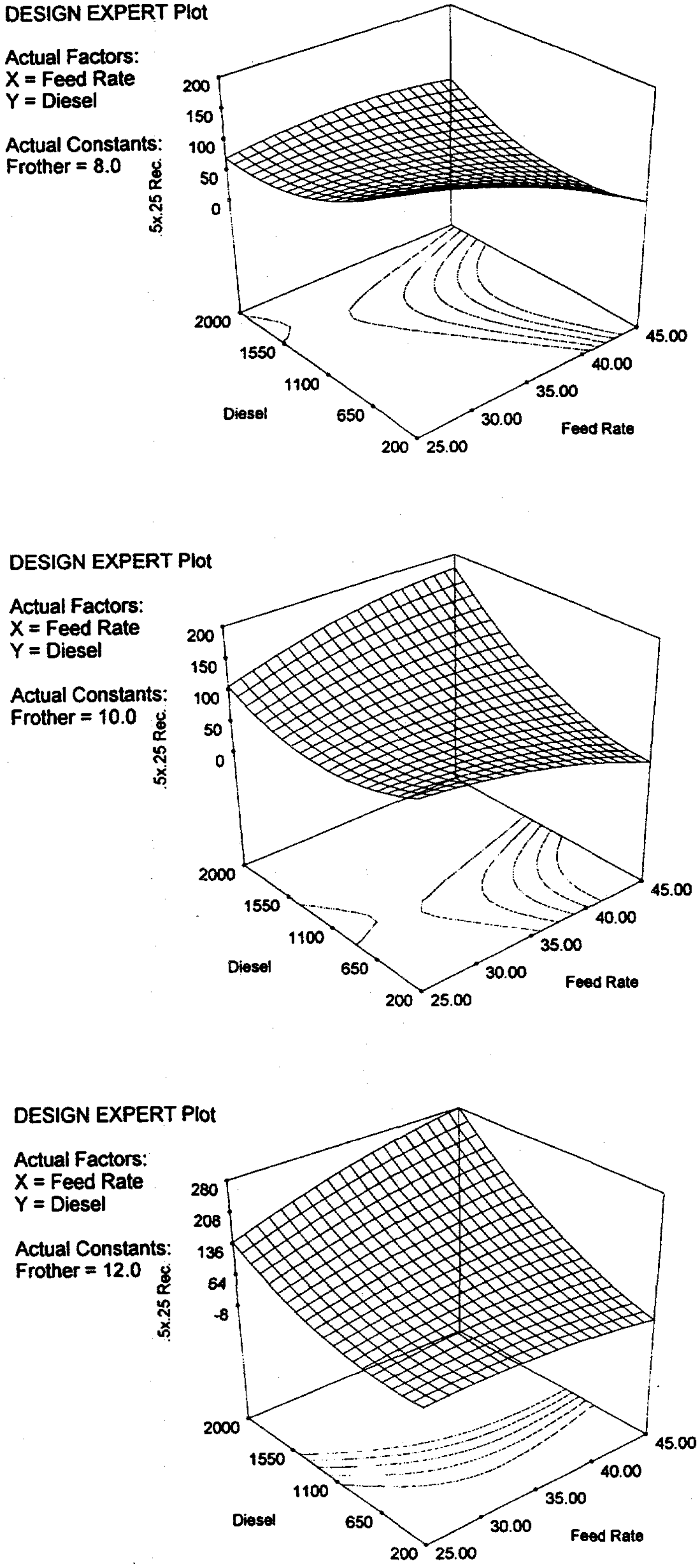


Figure B-2. 3D Response Plots, First Series (401-416) 0.50 x 0.25 mm Recovery

Table B-3. First Series (401-416) 0.50 mm x 0.

Response: Combined 0.50 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed Rate	kg/min	Numeric	25.00	45.00
B	Frother	ml/min	Numeric	8.00	12.00
C	Diesel	g/ton -.5mm	Numeric	200.00	2000.00

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	75948.47	1	75948.47		
Linear	1788.61	3	596.20	19.19	< 0.0001
Quadratic	247.57	6	41.26	1.98	0.2135
Cubic	125.16	6	20.86		
Residual	0.000	0			
Total	78109.81	16	4881.86		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	5.57	0.8275	0.7844	0.6304	798.83
Quadratic	4.57	0.9421	0.8552	-2.9196	8471.57
Cubic					

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-3 cont.

Response: Combined 0.50 mm x 0 Combustible Recovery

Factor	**Name**	**Units**	**Type**	**-1 Level**	**+1 Level**
A	Feed Rate	kg/min	Numeric	25.00	45.00
B	Frother	ml/min	Numeric	8.00	12.00
C	Diesel	g/ton -.5mm	Numeric	200.00	2000.00

ANOVA for Response Surface Quadratic Model:

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	2036.18	9	226.24	10.85	0.0045
Residual	125.16	6	20.86		
Cor Total	2161.34	15			

Root MSE	4.57	R-Squared	0.9421	
Dep Mean	68.90	Adj R-Squared	0.8552	
C.V.	6.63	Pred R-Squared	-2.9196	
PRESS	8471.57	Adeq Precision	10.276	Desire > 4

Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**t for H_0 Coeff=0**	**Prob > |t|**	**VIF**
Intercept	74.59	1	4.31			
A-Feed Rate	-9.65	1	4.19	-2.30	0.0607	7.60
B-Frother	4.87	1	3.30	1.48	0.1901	7.22
C-Diesel	14.04	1	7.02	2.00	0.0926	10.53
A^2	-3.39	1	6.58	-0.52	0.6250	5.73
B^2	-0.78	1	1.46	-0.53	0.6128	7.22
C^2	10.66	1	13.12	0.81	0.4475	12.02
AB	18.11	1	7.98	2.27	0.0637	15.53
AC	10.28	1	11.65	0.88	0.4114	13.43
BC	19.98	1	13.76	1.45	0.1965	23.90

Response: Combined 0.50 mm x 0 Recovery - Final Equation in Terms of Coded Factors:

0.50mmx0 Rec. =
+74.59
-9.65 * A
+4.87 * B

Table B-3 cont.

+14.04 * C
$-3.39 * A^2$
$-0.78 * B^2$
$+10.66 * C^2$
+18.11 * A * B
+10.28 * A * C
+19.98 * B * C

Response: Combined 0.50 mm x 0 Recovery - Final Equation in Terms of Actual Factors:

0.50mmx0 Rec. =
+504.84
-8.90 * Feed Rate
-37.58 * Frother
-0.16 * Diesel
$-0.034 * \text{Feed Rate}^2$
$-0.19 * \text{Frother}^2$
$+1.316\text{E-}05 * \text{Diesel}^2$
+0.91 * Feed Rate * Frother
+1.143E-03 * Feed Rate * Diesel
+0.011 * Frother * Diesel

Response: Combined 0.50 mm x 0 Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	70.62	64.29	6.33	0.411	1.807	0.228	2.443	3
2	62.74	61.43	1.31	0.388	0.367	0.009	0.339	9
3	83.16	84.19	-1.03	0.853	-0.585	0.198	-0.550	14
4	86.52	85.99	0.53	0.960	0.582	0.824	0.547	5
5	70.00	74.71	-4.71	0.258	-1.197	0.050	-1.252	1
6	80.22	78.82	1.40	0.904	0.985	0.909	0.982	7
7	72.00	70.93	1.07	0.718	0.440	0.049	0.408	2
8	68.16	66.46	1.70	0.393	0.478	0.015	0.445	10
9	48.70	48.88	-0.18	0.798	-0.090	0.003	-0.082	8
10	78.21	74.44	3.77	0.521	1.192	0.155	1.246	15
11	83.72	85.03	-1.31	0.906	-0.933	0.837	-0.921	16
12	58.67	62.68	-4.01	0.640	-1.462	0.380	-1.663	12
13	55.92	60.49	-4.57	0.301	-1.196	0.062	-1.250	4
14	75.46	75.89	-0.43	0.995	-1.338	35.422	-1.459	6
15	54.14	53.44	0.70	0.501	0.217	0.005	0.199	13
16	54.11	54.69	-0.58	0.454	-0.171	0.002	-0.156	11

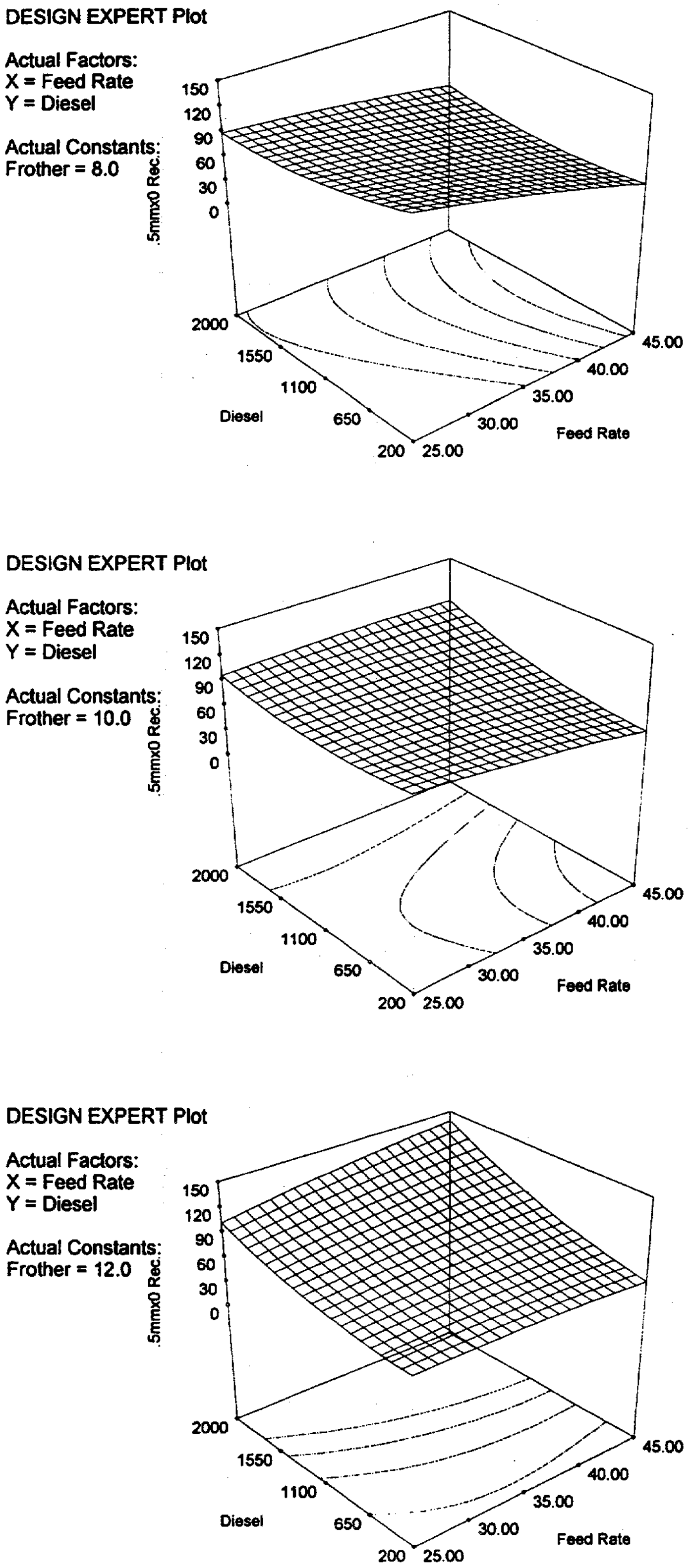


Figure B-3. 3D Response Plots, First Series (401-416) Combined 0.50 mm x 0 Rec

Table B-4. Second Series (451-465) 0.25 mm x 0

Response: 0.25 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Air Vg	cm/sec	Numeric	1.10	1.30
C	Frother	ml/min	Numeric	5.60	9.30

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	98575.45	1	98575.45		
Blocks	1.19	1	1.19		
Linear	105.67	3	35.22	2.16	0.1555
Quadratic	148.41	6	24.74	6.90	0.0413
Cubic	14.33	3	4.78	565.13	0.0309
Residual	8.450E-03	1	8.450E-03		
Total	98845.05	15	6589.67		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Lack of Fit Tests:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Linear	162.74	9	18.08	2139.86	0.0168
Quadratic	14.33	3	4.78	565.13	0.0309
Cubic	0.000	0	-		
Pure Error	8.450E-03	1	8.450E-03		

"Lack of Fit Tests": Want the selected model to have insignificant lack-of-fit.

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	4.03	0.3937	0.2118	-0.7181	461.17
Quadratic	1.89	0.9466	0.8264	-0.0892	292.36
Cubic	0.092	1.0000	0.9996		

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-4 cont.

Response: 0.25 mm x 0 Combustible Recovery

Factor	**Name**	**Units**	**Type**	**-1 Level**	**+1 Level**
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Air Vg	cm/sec	Numeric	1.10	1.30
C	Frother	ml/min	Numeric	5.60	9.30

ANOVA for Response Surface Quadratic Model:

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Block	1.19	1	1.19		
Model	254.08	9	28.23	7.88	0.0311
Residual	14.33	4	3.58		
Lack of Fit	*14.33*	*3*	*4.78*	*565.13*	*0.0309*
Pure Error	*8.450E-03*	*1*	*8.450E-03*		
Cor Total	269.60	14			

Root MSE	1.89	R-Squared	0.9466	
Dep Mean	81.07	Adj R-Squared	0.8264	
C.V.	2.34	Pred R-Squared	-0.0892	
PRESS	292.36	Adeq Precision	11.201	Desire > 4

Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**t for H_0 Coeff=0**	**Prob > |t|**	**VIF**
Intercept	83.26	1	1.75			
Block 1	3.64	1				
Block 2	-3.64					
A-Feed GPM	-3.25	1	0.93	-3.48	0.0254	1.95
B-Air Vg	-1.09	1	0.91	-1.20	0.2963	1.86
C-Frother	-1.09	1	0.73	-1.49	0.2097	1.86
A^2	3.29	1	1.31	2.51	0.0660	1.79
B^2	0.54	1	1.24	0.43	0.6867	1.59
C^2	-2.49	1	1.60	-1.55	0.1957	10.54
AB	-4.22	1	1.61	-2.62	0.0590	2.90
AC	-3.97	1	1.87	-2.12	0.1009	6.58
BC	1.14	1	1.15	0.99	0.3801	2.07

Table B-4 cont.

Response: 0.25 mm x 0 Rec - Final Equation in Terms of Coded Factors:

0.25mmx0 Rec =

+83.26
-3.25 * A
-1.09 * B
-1.09 * C
+3.29 * A^2
+0.54 * B^2
-2.49 * C^2
-4.22 * A * B
-3.97 * A * C
+1.14 * B * C

Response: 0.25 mm x 0 Rec - Final Equation in Terms of Actual Factors:

0.25mmx0 Rec =

-41.84
+3.05 * Feed GPM
+25.36 * Air Vg
+13.58 * Frother
+0.033 * Feed GPM^2
+53.66 * Air Vg^2
-0.73 * Frother^2
-4.22 * Feed GPM * Air Vg
-0.21 * Feed GPM * Frother
+6.15 * Air Vg * Frother

Response: 0.25 mm x 0 Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	81.47	80.68	0.79	0.848	1.074	0.585	1.103	11
2	79.12	78.57	0.55	0.847	0.748	0.281	0.699	10
3	84.61	85.14	-0.53	0.798	-0.625	0.140	-0.569	13
4	81.70	82.47	-0.77	0.890	-1.223	1.097	-1.339	2
5	82.38	82.53	-0.15	0.984	-0.631	2.231	-0.576	1
6	82.20	81.84	0.36	0.872	0.527	0.172	0.473	12
7	86.12	86.23	-0.11	0.655	-0.100	0.002	-0.086	14
8	82.21	79.59	2.62	0.350	1.718	0.144	2.909	15
9	67.93	68.07	-0.14	0.962	-0.384	0.337	-0.339	6
10	80.36	81.47	-1.11	0.659	-1.004	0.177	-1.005	9
11	84.17	83.54	0.63	0.735	0.650	0.106	0.595	5
12	83.58	83.82	-0.24	0.862	-0.337	0.064	-0.296	3
13	84.57	83.90	0.67	0.898	1.102	0.974	1.143	4
14	77.85	79.07	-1.22	0.321	-0.784	0.026	-0.738	8
15	77.72	79.07	-1.35	0.321	-0.867	0.032	-0.833	7

Note: Predicted values include block corrections.

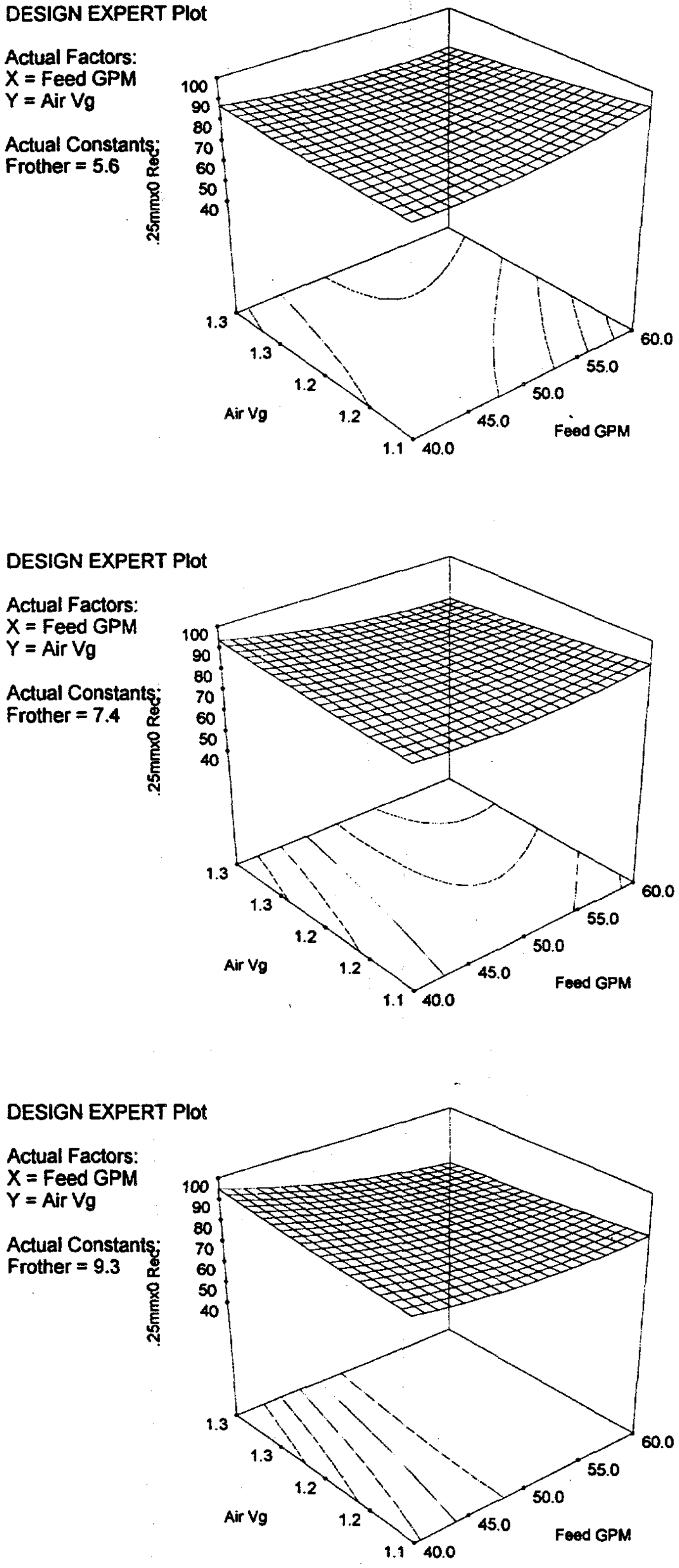


Figure B-4. 3D Response Plots, Second Series (451-465) 0.25 mm x 0 Rec

Table B-5. Second Series (451-465) 0.50x0.25 mm

Response: 0.50x0.25 mm Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Air Vg	cm/sec	Numeric	1.10	1.30
C	Frother	ml/min	Numeric	5.60	9.30

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	67648.93	1	67648.93		
Blocks	243.31	1	243.31		
Linear	977.83	3	325.94	1.57	0.2575
Quadratic	1763.09	6	293.85	3.75	0.1109
Cubic	311.34	3	103.78	42.11	0.1127
Residual	2.46	1	2.46		
Total	70946.96	15	4729.80		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Lack of Fit Tests:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Linear	2074.42	9	230.49	93.54	0.0801
Quadratic	311.34	3	103.78	42.11	0.1127
Cubic	0.000	0			
Pure Error	2.46	1	2.46		

"Lack of Fit Tests": Want the selected model to have insignificant lack-of-fit.

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	14.41	0.3201	0.1161	-0.5218	4648.67
Quadratic	8.86	0.8973	0.6661	-4.8765	17950.97
Cubic	1.57	0.9992	0.9895		

Case(s) with leverage of 1.0000: PRESS statistic not defined

Table B-5 cont.

Response: 0.50x0.25 mm Combustible Recovery

Factor	**Name**	**Units**	**Type**	**-1 Level**	**+1 Level**
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Air Vg	cm/sec	Numeric	1.10	1.30
C	Frother	ml/min	Numeric	5.60	9.30

ANOVA for Response Surface Quadratic Model:

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Block	243.31	1	243.31		
Model	2740.92	9	304.55	3.88	0.1022
Residual	313.80	4	78.45		
Lack of Fit	*311.34*	*3*	*103.78*	*42.11*	*0.1127*
Pure Error	*2.46*	*1*	*2.46*		
Cor Total	3298.03	14			

Root MSE	8.86	R-Squared	0.8973	
Dep Mean	67.16	Adj R-Squared	0.6661	
C.V.	13.19	Pred R-Squared	-4.8765	
PRESS	17950.97	Adeq Precision	7.886	Desire > 4

Factor	**Coefficient Estimate**	**DF**	**Standard Error**	**t for H_0 Coeff=0**	**Prob > |t|**	**VIF**
Intercept	61.55	1	8.18			
Block 1	4.78	1				
Block 2	-4.78					
A-Feed GPM	-0.47	1	4.37	-0.11	0.9187	1.95
B-Air Vg	-2.98	1	4.27	-0.70	0.5239	1.86
C-Frother	-7.33	1	3.42	-2.14	0.0990	1.86
A^2	17.86	1	6.13	2.91	0.0435	1.79
B^2	9.02	1	5.79	1.56	0.1940	1.59
C^2	-1.28	1	7.50	-0.17	0.8725	10.54
AB	-16.92	1	7.54	-2.24	0.0884	2.90
AC	-18.31	1	8.74	-2.09	0.1043	6.58
BC	6.51	1	5.40	1.20	0.2947	2.07

Table B-5 cont.

Response: 0.50x0.25 mm Rec - Final Equation in Terms of Coded Factors:

0.50x0.25 Rec =

$$
\begin{aligned}
&+61.55\\
&-0.47 * A\\
&-2.98 * B\\
&-7.33 * C\\
&+17.86 * A^2\\
&+9.02 * B^2\\
&-1.28 * C^2\\
&-16.92 * A * B\\
&-18.31 * A * C\\
&+6.51 * B * C
\end{aligned}
$$

Response: 0.50x0.25 mm Rec - Final Equation in Terms of Actual Factors:

0.50x0.25 Rec =

$$
\begin{aligned}
&+784.34\\
&+9.77 * \text{Feed GPM}\\
&-1610.50 * \text{Air Vg}\\
&+8.91 * \text{Frother}\\
&+0.18 * \text{Feed GPM}^2\\
&+901.88 * \text{Air Vg}^2\\
&-0.37 * \text{Frother}^2\\
&-16.92 * \text{Feed GPM} * \text{Air Vg}\\
&-0.99 * \text{Feed GPM} * \text{Frother}\\
&+35.18 * \text{Air Vg} * \text{Frother}
\end{aligned}
$$

Response: 0.50x0.25 mm Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	65.38	65.88	-0.50	0.848	-0.146	0.011	-0.127	11
2	77.07	75.22	1.85	0.847	0.532	0.142	0.478	10
3	80.42	83.57	-3.15	0.798	-0.791	0.225	-0.746	13
4	73.59	74.39	-0.80	0.890	-0.270	0.054	-0.236	2
5	61.99	63.89	-1.90	0.984	-1.699	16.155	-2.787	1
6	87.06	89.60	-2.54	0.872	-0.802	0.398	-0.758	12
7	80.95	75.40	5.55	0.655	1.067	0.196	1.092	14
8	67.97	56.57	11.40	0.350	1.596	0.125	2.295	15
9	31.27	29.78	1.49	0.962	0.859	1.685	0.823	6
10	80.21	78.82	1.39	0.659	0.269	0.013	0.235	9
11	75.88	71.81	4.07	0.735	0.891	0.200	0.862	5
12	60.47	63.20	-2.73	0.862	-0.829	0.389	-0.789	3
13	70.14	70.26	-0.12	0.898	-0.044	0.002	-0.038	4
14	48.58	54.47	-5.89	0.321	-0.807	0.028	-0.764	8
15	46.36	54.47	-8.11	0.321	-1.111	0.053	-1.157	7

Note: Predicted values include block corrections.

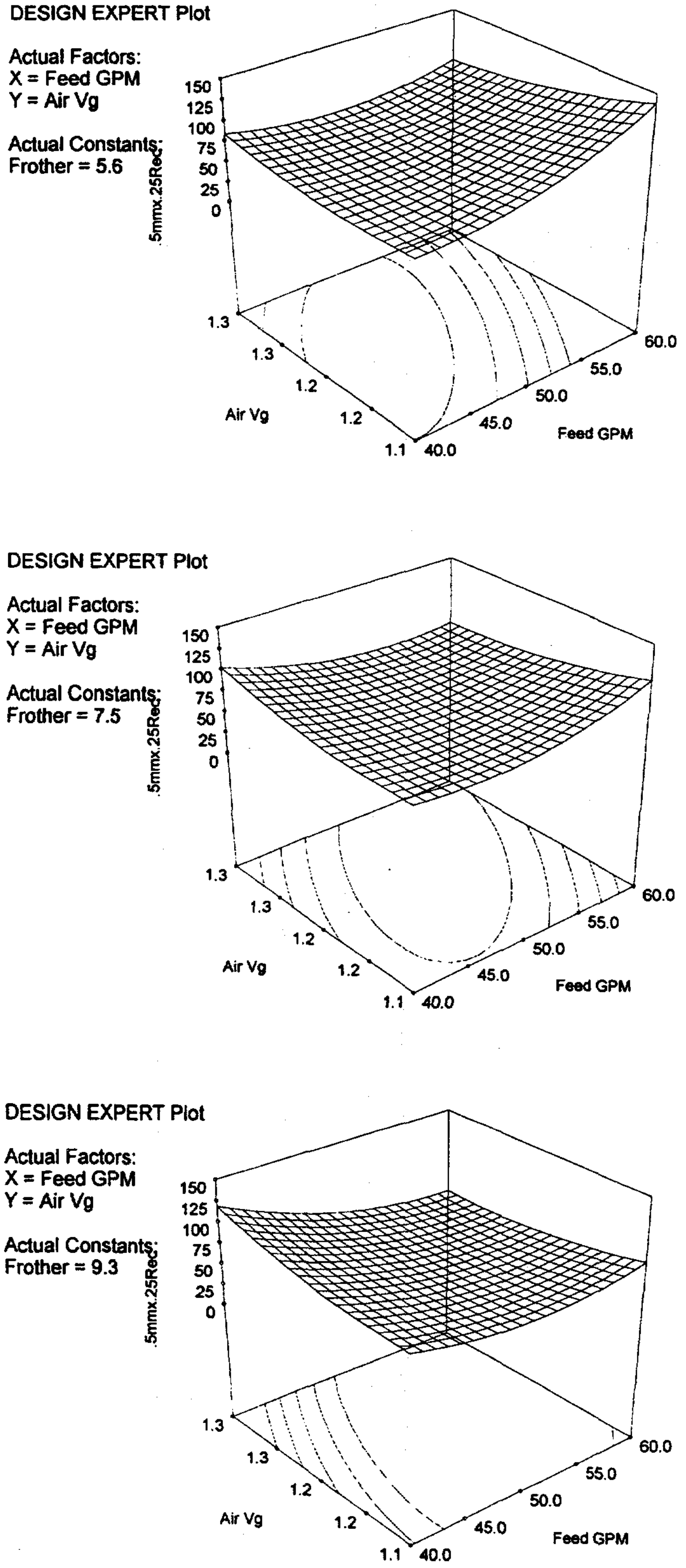


Figure B-5. 3D Response Plots, Second Series (451-465) 0.50x0.25 mm Recovery

Table B-6. Second Series (451-465) 0.50 mm x 0

Response: Combined 0.50 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Air Vg	cm/sec	Numeric	1.10	1.30
C	Frother	ml/min	Numeric	5.60	9.30

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	93991.42	1	93991.42		
Blocks	12.48	1	12.48		
Linear	153.26	3	51.09	1.77	0.2165
Quadratic	258.47	6	43.08	5.67	0.0574
Cubic	30.31	3	10.10	147.62	0.0604
Residual	0.068	1	0.068		
Total	94446.01	15	6296.40		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Lack of Fit Tests:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Linear	288.79	9	32.09	468.78	0.0358
Quadratic	30.31	3	10.10	147.62	0.0604
Cubic	0.000	0			
Pure Error	0.068	1	0.068		

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	5.37	0.3466	0.1506	-0.7578	777.15
Quadratic	2.76	0.9313	0.7767	-0.6719	739.16
Cubic	0.26	0.9998	0.9980		

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-6 cont.

Response: Combined 0.50 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Air Vg	cm/sec	Numeric	1.10	1.30
C	Frother	ml/min	Numeric	5.60	9.30

ANOVA for Response Surface Quadratic Model:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Block	12.48	1	12.48		
Model	411.73	9	45.75	6.02	0.0497
Residual	30.38	4	7.60		
Lack of Fit	*30.31*	*3*	*10.10*	*147.62*	*0.0604*
Pure Error	*0.068*	*1*	*0.068*		
Cor Total	454.59	14			

Root MSE	2.76	R-Squared	0.9313	
Dep Mean	79.16	Adj R-Squared	0.7767	
C.V.	3.48	Pred R-Squared	-0.6719	
PRESS	739.16	Adeq Precision	9.759	Desire > 4

Factor	Coefficient Estimate	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|	VIF
Intercept	81.16	1	2.55			
Block 1	4.22	1				
Block 2	-4.22					
A-Feed GPM	-2.90	1	1.36	-2.13	0.1001	1.95
B-Air Vg	-1.70	1	1.33	-1.28	0.2697	1.86
C-Frother	-2.12	1	1.07	-1.99	0.1177	1.86
A^2	5.19	1	1.91	2.72	0.0529	1.79
B^2	0.98	1	1.80	0.54	0.6163	1.59
C^2	-2.71	1	2.33	-1.16	0.3101	10.54
AB	-6.39	1	2.35	-2.72	0.0528	2.90
AC	-6.00	1	2.72	-2.21	0.0919	6.58
BC	2.09	1	1.68	1.24	0.2818	2.07

Response: Combined 0.50 mm x 0 Rec -- Final Equation in Terms of Coded Factors:

0.50 mm x 0 Rec =
+81.16
-2.90 * A

Table B-6 cont.

$$
\begin{aligned}
&-1.70 \ * B \\
&-2.12 \ * C \\
&+5.19 \ * A^2 \\
&+0.98 \ * B^2 \\
&-2.71 \ * C^2 \\
&-6.39 \ * A * B \\
&-6.00 \ * A * C \\
&+2.09 \ * B * C
\end{aligned}
$$

Response: Combined 0.50 mm x 0 Rec - Final Equation in Terms of Actual Factors:

0.50 mm x 0 Rec =

$$
\begin{aligned}
&-52.50 \\
&+4.61 \ * \text{Feed GPM} \\
&-15.90 \ * \text{Air Vg} \\
&+13.33 \ * \text{Frother} \\
&+0.052 \ * \text{Feed GPM}^2 \\
&+97.66 \ * \text{Air Vg}^2 \\
&-0.79 \ * \text{Frother}^2 \\
&-6.39 \ * \text{Feed GPM} * \text{Air Vg} \\
&-0.32 \ * \text{Feed GPM} * \text{Frother} \\
&+11.29 \ * \text{Air Vg} * \text{Frother}
\end{aligned}
$$

Response: Combined 0.50 mm x 0 Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	79.35	78.25	1.10	0.848	1.028	0.536	1.038	11
2	78.84	77.85	0.99	0.847	0.920	0.425	0.897	10
3	83.32	84.36	-1.04	0.798	-0.837	0.252	-0.798	13
4	79.88	81.03	-1.15	0.890	-1.253	1.153	-1.393	2
5	80.11	80.38	-0.27	0.984	-0.779	3.395	-0.732	1
6	83.57	83.24	0.33	0.872	0.334	0.069	0.294	12
7	85.34	85.14	0.20	0.655	0.125	0.003	0.109	14
8	80.55	76.89	3.66	0.350	1.647	0.133	2.515	15
9	61.93	62.11	-0.18	0.962	-0.325	0.241	-0.285	6
10	79.75	81.26	-1.51	0.659	-0.937	0.154	-0.918	9
11	82.91	81.68	1.23	0.735	0.867	0.189	0.834	5
12	80.55	81.14	-0.59	0.862	-0.575	0.187	-0.520	3
13	82.87	81.92	0.95	0.898	1.082	0.939	1.114	4
14	74.39	76.08	-1.69	0.321	-0.743	0.024	-0.693	8
15	74.02	76.08	-2.06	0.321	-0.906	0.035	-0.880	7

Note: Predicted values include block corrections.

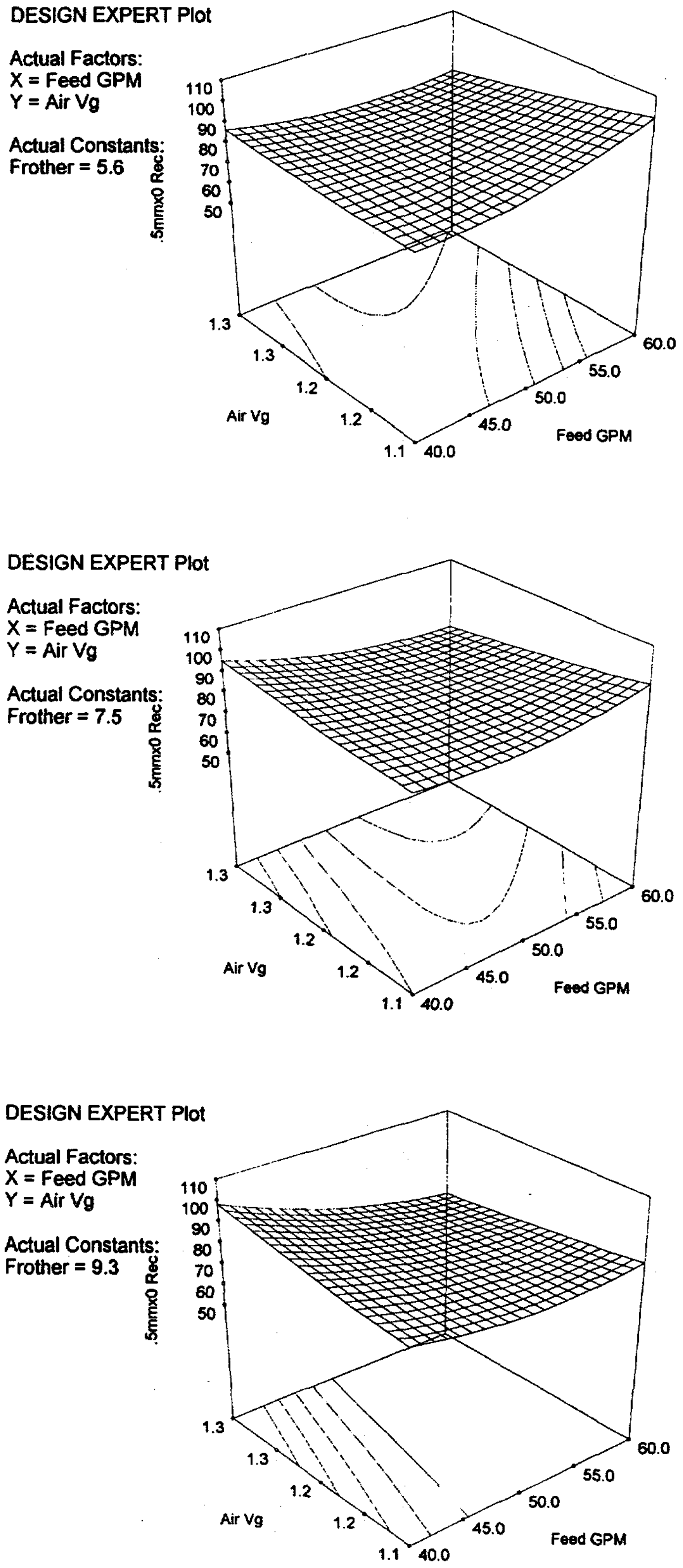


Figure B-6. 3D Response Plots, Second Series (451-465) 0.50 mm x 0 Recovery

Table B-7. Second Series Revisited (451-465) 0.25 mm x 0

Response: 0.25 mm x 0 Combustible Recovery

Factor	**Name**	**Units**	**Type**	**-1 Level**	**+1 Level**
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Diesel	g/T (-.5mm)	Numeric	700.00	1400.00
C	Frother	ml/min	Numeric	5.60	9.30

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Mean	98575.45	1	98575.45		
Blocks	1.19	1	1.19		
Linear	98.39	3	32.80	1.93	0.1889
Quadratic	134.23	6	22.37	2.50	0.1971
Cubic	35.79	4	8.95		
Residual	0.000	0			
Total	98845.05	15	6589.67		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Model Summary Statistics:

Source	**Root MSE**	**R-Squared**	**Adjusted R-Squared**	**Predicted R-Squared**	**PRESS**
Linear	4.12	0.3666	0.1765	-0.7193	461.48
Quadratic	2.99	0.8667	0.5667	-5.7482	1811.32
Cubic					

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-7 cont.

Response: 0.25 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Diesel	g/T (-.5mm)	Numeric	700.00	1400.00
C	Frother	ml/min	Numeric	5.60	9.30

ANOVA for Response Surface Quadratic Model:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Block	1.19	1	1.19		
Model	232.63	9	25.85	2.89	0.1597
Residual	35.79	4	8.95		
Cor Total	269.60	14			

Root MSE	2.99	R-Squared	0.8667	
Dep Mean	81.07	Adj R-Squared	0.5667	
C.V.	3.69	Pred R-Squared	-5.7482	
PRESS	1811.32	Adeq Precision	6.463	Desire > 4

Factor	Coefficient Estimate	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|	VIF
Intercept	86.29	1	3.38			
Block 1	4.28	1				
Block 2	-4.28					
A-Feed GPM	-2.19	1	1.68	-1.30	0.2643	2.54
B-Diesel	-0.63	1	2.67	-0.24	0.8237	7.69
C-Frother	-1.90	1	1.75	-1.09	0.3379	4.25
A^2	0.66	1	2.70	0.25	0.8180	3.04
B^2	-1.84	1	2.78	-0.66	0.5442	1.88
C^2	-5.29	1	3.67	-1.44	0.2236	22.20
AB	-3.31	1	2.85	-1.16	0.3094	3.86
AC	1.59	1	4.94	0.32	0.7639	18.42
BC	2.87	1	2.50	1.15	0.3150	6.05

Response: 0.25 mm x 0 Rec - Final Equation in Terms of Coded Factors:

0.25 mm x 0 Rec =

+86.29
-2.19 * A
-0.63 * B

Table B-7 cont.

$-1.90 * C$
$+0.66 * A^2$
$-1.84 * B^2$
$-5.29 * C^2$
$-3.31 * A * B$
$+1.59 * A * C$
$+2.87 * B * C$

Response: 0.25 mm x 0 Rec - Final Equation in Terms of Actual Factors:

0.25 mm x 0 Rec =
+37.98
-0.53 * Feed GPM
+0.044 * Diesel
+13.05 * Frother
$+6.636E-03 * \text{Feed GPM}^2$
$-1.501E-05 * \text{Diesel}^2$
$-1.54 * \text{Frother}^2$
-9.466E-04 * Feed GPM * Diesel
+0.086 * Feed GPM * Frother
+4.426E-03 * Diesel * Frother

Response: 0.25 mm x 0 Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	81.47	84.35	-2.88	0.500	-1.362	0.168	-1.611	11
2	79.12	76.55	2.57	0.752	1.725	0.822	2.951	10
3	84.61	82.46	2.15	0.787	1.558	0.813	2.152	13
4	81.70	83.39	-1.69	0.877	-1.612	1.685	-2.358	2
5	82.38	82.45	-0.065	0.936	-0.086	0.010	-0.074	1
6	82.20	82.24	-0.036	0.948	-0.053	0.005	-0.046	12
7	86.12	85.33	0.79	0.792	0.581	0.117	0.526	14
8	82.21	80.88	1.33	0.283	0.526	0.010	0.472	15
9	67.93	68.77	-0.84	0.953	-1.299	3.118	-1.480	6
10	80.36	81.37	-1.01	0.649	-0.570	0.055	-0.515	9
11	84.17	82.25	1.92	0.809	1.471	0.835	1.881	5
12	83.58	83.93	-0.35	0.987	-1.030	7.595	-1.041	3
13	84.57	83.55	1.02	0.919	1.200	1.492	1.299	4
14	77.85	79.58	-1.73	0.301	-0.692	0.019	-0.638	8
15	77.72	78.91	-1.19	0.506	-0.566	0.030	-0.511	7

Note: Predicted values include block corrections.

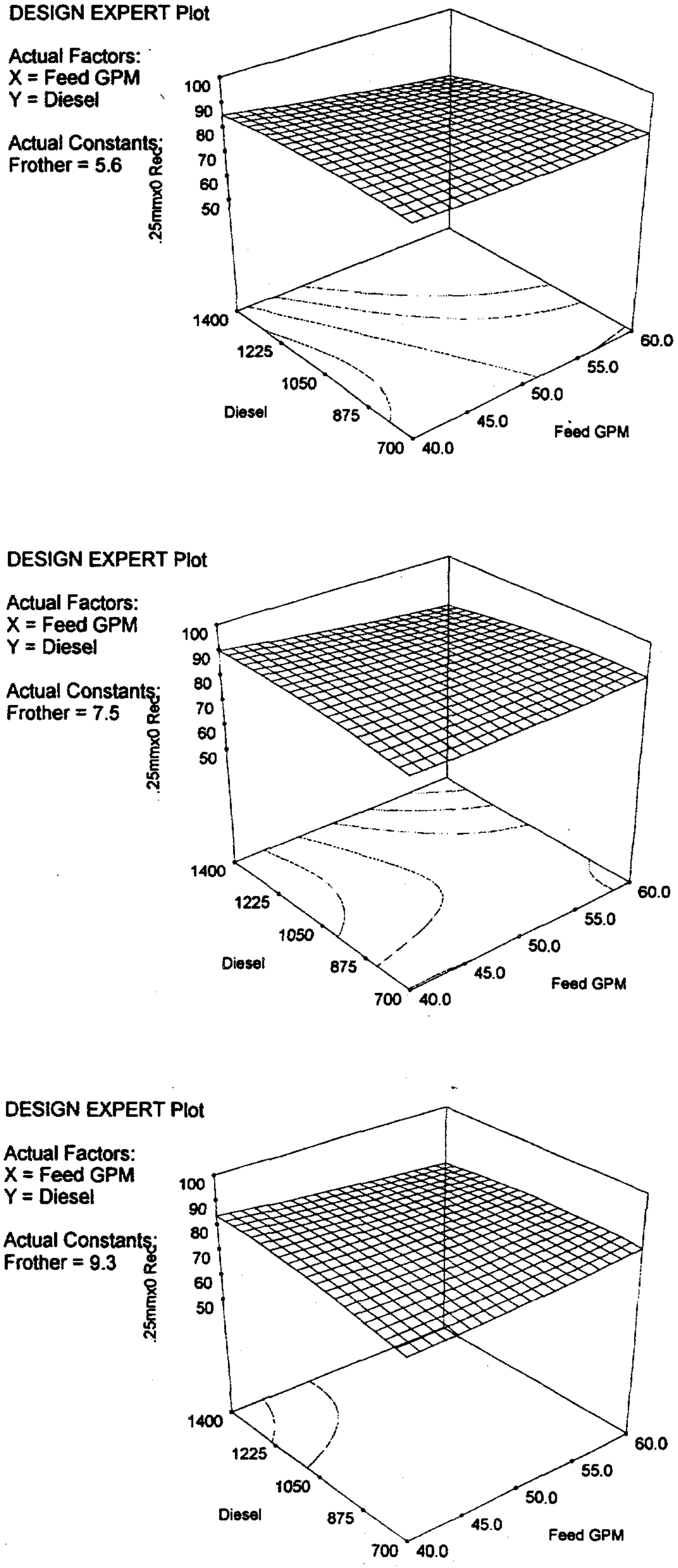


Figure B-7. 3D Response Plots, Second Series Revisited (451-465) 0.25 mm x 0 Rec

Table B-8. Second Series Revisited (451-465) 0.50x0.25 mm

Response: 0.50x0.25 mm Combustible Recovery

Factor	**Name**	**Units**	**Type**	**-1 Level**	**+1 Level**
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Diesel	g/T (-.5mm)	Numeric	700.00	1400.00
C	Frother	ml/min	Numeric	5.60	9.30

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	67648.93	1	67648.93		
Blocks	243.31	1	243.31		
Linear	1123.12	3	374.37	1.94	0.1875
Quadratic	1205.86	6	200.98	1.11	0.4825
Cubic	725.74	4	181.44		
Residual	0.000	0			
Total	70946.96	15	4729.80		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Model Summary Statistics:

Source	**Root MSE**	**R-Squared**	**Adjusted R-Squared**	**Predicted R-Squared**	**PRESS**
Linear	13.90	0.3677	0.1780	-0.5432	4714.02
Quadratic	13.47	0.7624	0.2279	-11.3740	37799.02
Cubic					

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table B-8 cont.

Response: 0.50x0.25 mm Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Diesel	g/T (-.5mm)	Numeric	700.00	1400.00
C	Frother	ml/min	Numeric	5.60	9.30

ANOVA for Response Surface Quadratic Model:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Block	243.31	1	243.31		
Model	2328.98	9	258.78	1.43	0.3895
Residual	725.74	4	181.44		
Cor Total	3298.03	14			

Root MSE	13.47	R-Squared	0.7624	
Dep Mean	67.16	Adj R-Squared	0.2279	
C.V.	20.06	Pred R-Squared	-11.3740	
PRESS	37799.02	Adeq Precision	4.644	Desire > 4

Factor	Coefficient Estimate	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|	VIF
Intercept	83.31	1	15.24			
Block 1	4.98	1				
Block 2	-4.98					
A-Feed GPM	5.94	1	7.59	0.78	0.4772	2.54
B-Diesel	4.77	1	12.01	0.40	0.7112	7.69
C-Frother	-16.63	1	7.88	-2.11	0.1023	4.25
A^2	0.24	1	12.16	0.020	0.9850	3.04
B^2	-11.09	1	12.51	-0.89	0.4255	1.88
C^2	-15.67	1	16.55	-0.95	0.3973	22.20
AB	-9.03	1	12.83	-0.70	0.5204	3.86
AC	7.14	1	22.24	0.32	0.7642	18.42
BC	16.78	1	11.24	1.49	0.2099	6.05

Response: 0.50x0.25 mm Rec - Final Equation in Terms of Coded Factors:

0.50x0.25 mm Rec =

+83.31

+5.94 * A

Table B-8 cont.

+4.77 * B
-16.63 * C
+0.24 * A^2
-11.09 * B^2
-15.67 * C^2
-9.03 * A * B
+7.14 * A * C
+16.78 * B * C

Response: 0.50x0.25 mm Rec - Final Equation in Terms of Actual Factors:

0.50x0.25 mm Rec =
-30.42
+0.18 * Feed GPM
+0.14 * Diesel
+12.71 * Frother
+2.429E-03 * Feed GPM^2
-9.049E-05 * Diesel^2
-4.58 * Frother^2
-2.579E-03 * Feed GPM * Diesel
+0.39 * Feed GPM * Frother
+0.026 * Diesel * Frother

Response: 0.50x0.25 mm Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	65.38	81.23	-15.85	0.500	-1.664	0.252	-2.598	11
2	77.07	65.31	11.76	0.752	1.755	0.850	3.167	10
3	80.42	72.02	8.40	0.787	1.350	0.611	1.585	13
4	73.59	79.77	-6.18	0.877	-1.309	1.112	-1.500	2
5	61.99	60.68	1.31	0.936	0.384	0.195	0.339	1
6	87.06	88.74	-1.68	0.948	-0.548	0.502	-0.494	12
7	80.95	74.81	6.14	0.792	0.998	0.344	0.998	14
8	67.97	63.38	4.59	0.283	0.402	0.006	0.356	15
9	31.27	35.17	-3.90	0.953	-1.337	3.305	-1.558	6
10	80.21	80.75	-0.54	0.649	-0.067	0.001	-0.058	9
11	75.88	69.39	6.49	0.809	1.104	0.470	1.146	5
12	60.47	62.12	-1.65	0.987	-1.096	8.605	-1.135	3
13	70.14	66.20	3.94	0.919	1.028	1.095	1.039	4
14	48.58	56.70	-8.12	0.301	-0.721	0.020	-0.669	8
15	46.36	51.06	-4.70	0.506	-0.497	0.023	-0.444	7

Note: Predicted values include block corrections.

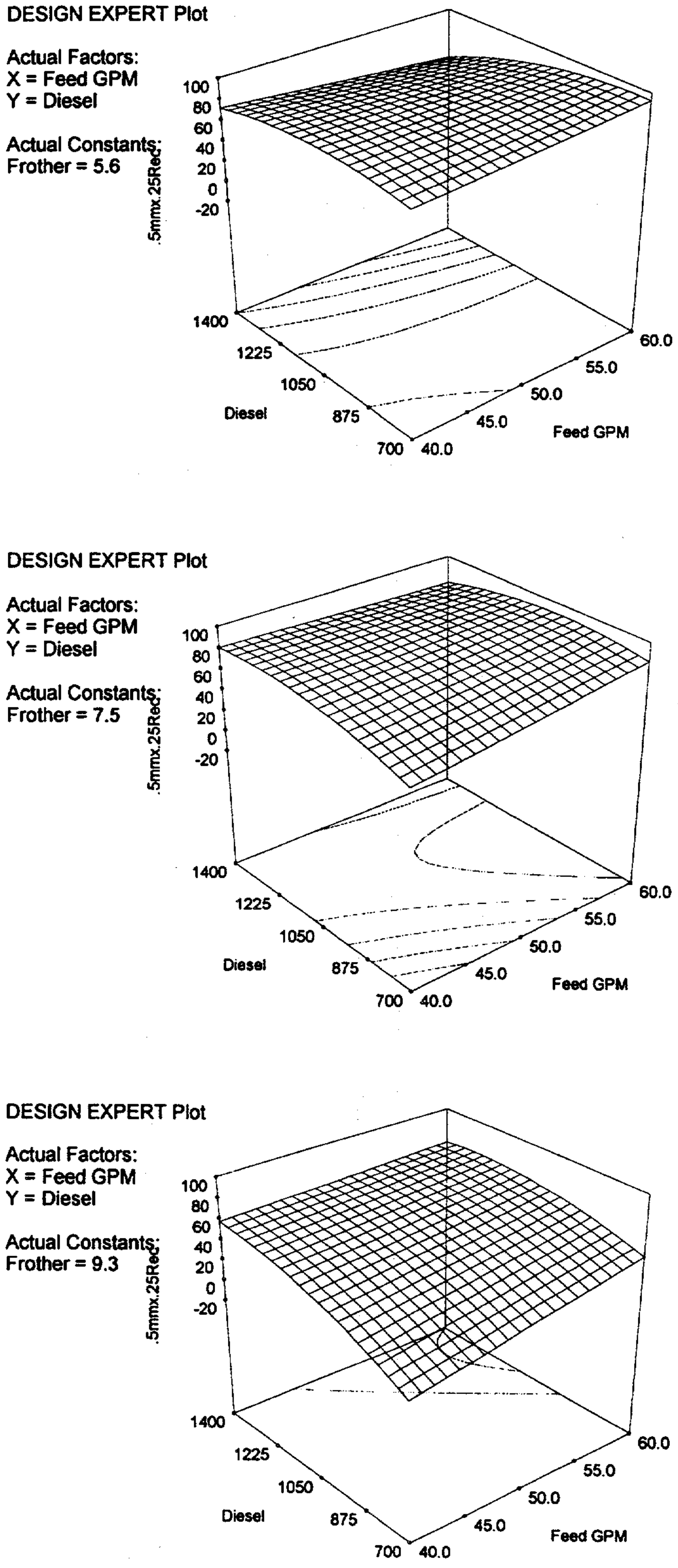


Figure B-8. 3D Response Plots, Second Series Revisited (451-465) 0.50x0.25 mm Rec

Table B-9. Second Series Revisited (451-465) 0.50 mm x 0

Response: Combined 0.50 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Diesel	g/T (-.5mm)	Numeric	700.00	1400.00
C	Frother	ml/min	Numeric	5.60	9.30

***** WARNING: The Cubic Model is Aliased! *****

Sequential Model Sum of Squares:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Mean	93991.42	1	93991.42		
Blocks	12.48	1	12.48		
Linear	148.71	3	49.57	1.69	0.2318
Quadratic	218.50	6	36.42	1.94	0.2707
Cubic	74.90	4	18.72		
Residual	0.000	0			
Total	94446.01	15	6296.40		

"Sequential Model Sum of Squares": Select the highest order polynomial where the additional terms are significant.

Model Summary Statistics:

Source	Root MSE	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	5.42	0.3364	0.1373	-0.7723	783.57
Quadratic	4.33	0.8306	0.4494	-7.8506	3912.96
Cubic					

Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model minimizing the "PRESS", or equivalently maximizing the "PRED R-SQR".

Table 9 cont.

Response: Combined 0.50 mm x 0 Combustible Recovery

Factor	Name	Units	Type	-1 Level	+1 Level
A	Feed GPM	gpm	Numeric	40.00	60.00
B	Diesel	g/T (-.5mm)	Numeric	700.00	1400.00
C	Frother	ml/min	Numeric	5.60	9.30

ANOVA for Response Surface Quadratic Model:

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Block	12.48	1	12.48		
Model	367.21	9	40.80	2.18	0.2356
Residual	74.90	4	18.72		
Cor Total	454.59	14			

Root MSE	4.33	R-Squared	0.8306	
Dep Mean	79.16	Adj R-Squared	0.4494	
C.V.	5.47	Pred R-Squared	-7.8506	
PRESS	3912.96	Adeq Precision	5.627	Desire > 4

Factor	Coefficient Estimate	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|	VIF
Intercept	85.79	1	4.90			
Block 1	4.57	1				
Block 2	-4.57					
A-Feed GPM	-1.18	1	2.44	-0.48	0.6532	2.54
B-Diesel	-0.17	1	3.86	-0.044	0.9673	7.69
C-Frother	-3.54	1	2.53	-1.40	0.2345	4.25
A^2	0.75	1	3.91	0.19	0.8581	3.04
B^2	-2.66	1	4.02	-0.66	0.5436	1.88
C^2	-6.94	1	5.32	-1.31	0.2617	22.20
AB	-5.03	1	4.12	-1.22	0.2895	3.86
AC	2.47	1	7.15	0.35	0.7472	18.42
BC	4.51	1	3.61	1.25	0.2797	6.05

Response: Combined 0.50 mm x 0 Rec - Final Equation in Terms of Coded Factors:

0.50 mm x 0 Rec =

+85.79

Table B-9 cont.

-1.18 * A
-0.17 * B
-3.54 * C
+0.75 * A^2
-2.66 * B^2
-6.94 * C^2
-5.03 * A * B
+2.47 * A * C
+4.51 * B * C

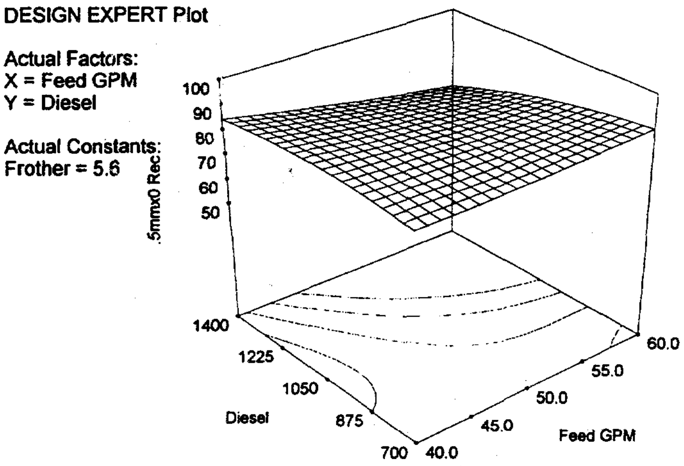
Response: Combined 0.50 mm x 0 Rec - Final Equation in Terms of Actual Factors:

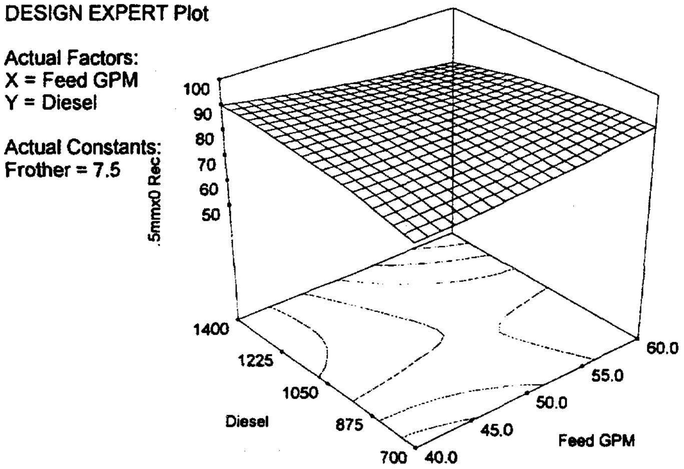
0.5 mm x 0 Rec =
+17.38
-0.35 * Feed GPM
+0.065 * Diesel
+14.31 * Frother
+7.450E-03 * Feed GPM^2
-2.175E-05 * Diesel^2
-2.03 * Frother^2
-1.436E-03 * Feed GPM * Diesel
+0.13 * Feed GPM * Frother
+6.970E-03 * Diesel * Frother

Response: Combined 0.50 mm x 0 Rec - Diagnostics Case Statistics:

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	79.35	83.75	-4.40	0.500	-1.439	0.188	-1.795	11
2	78.84	75.05	3.79	0.752	1.759	0.854	3.201	10
3	83.32	80.23	3.09	0.787	1.546	0.801	2.112	13
4	79.88	82.26	-2.38	0.877	-1.569	1.596	-2.190	2
5	80.11	80.09	0.016	0.936	0.014	0.000	0.012	1
6	83.57	83.72	-0.15	0.948	-0.149	0.037	-0.130	12
7	85.34	84.04	1.30	0.792	0.656	0.149	0.602	14
8	80.55	78.85	1.70	0.283	0.463	0.008	0.412	15
9	61.93	63.19	-1.26	0.953	-1.346	3.345	-1.575	6
10	79.75	80.95	-1.20	0.649	-0.467	0.037	-0.416	9
11	82.91	80.25	2.66	0.809	1.407	0.763	1.714	5
12	80.55	81.06	-0.51	0.987	-1.059	8.032	-1.081	3
13	82.87	81.39	1.48	0.919	1.204	1.501	1.306	4
14	74.39	76.83	-2.44	0.301	-0.675	0.018	-0.621	8
15	74.02	75.70	-1.68	0.506	-0.553	0.029	-0.498	7

Note: Predicted values include block corrections.





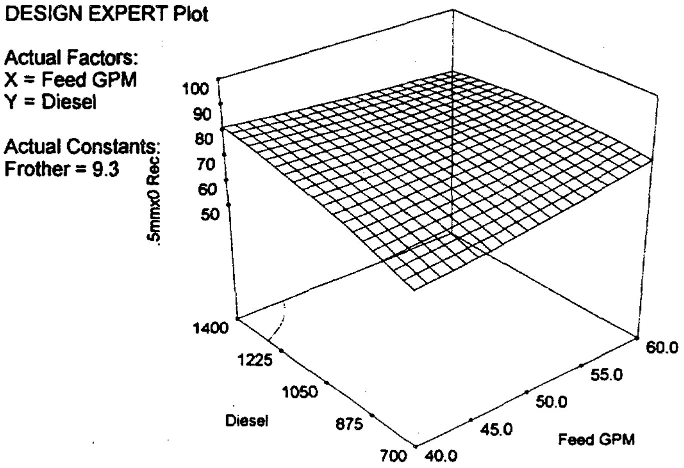


Figure B-9. 3D Response Plots, Second Series Revisited (451-465) 0.50 mm x 0 Rec